

FELIPE SILVA DOS SANTOS

**AN EXPERIMENTAL STUDY ON HEAT TRANSFER OF
NANOFLUID FLOWING IN SUDDEN EXPANSION OR
CONTRACTION**



**FEDERAL UNIVERSITY OF UBERLÂNDIA
DEPARTAMENT OF MECHANICAL ENGINEERING**

2024

FELIPE SILVA DOS SANTOS

**AN EXPERIMENTAL STUDY ON HEAT TRANSFER OF
NANOFLUID FLOWING IN SUDDEN EXPANSION OR
CONTRACTION**

Thesis submitted to the Graduate Program in Mechanical Engineering at the Federal University of Uberlândia in partial fulfillment of the requirements to obtain the degree of **DOCTOR IN MECHANICAL ENGINEERING**.

Concentration area: Heat Transfer and Fluid Mechanics

Advisor: Prof. Dr. Enio Pedone Bandarra Filho

Co-Advisor: Prof. Dr. Mohammad Reza Safaei

UBERLÂNDIA – MG

2024

Ficha Catalográfica Online do Sistema de Bibliotecas da UFU
com dados informados pelo(a) próprio(a) autor(a).

S237
2024

Santos, Felipe Silva dos, 1991-
An experimental study on heat transfer of nanofluid
flowing in sudden expansion or contraction [recurso
eletrônico] / Felipe Silva dos Santos. - 2024.

Orientador: Enio Pedone Bandarra Filho.

Coorientador: Mohammad Reza Safaei.

Tese (Doutorado) - Universidade Federal de Uberlândia,
Pós-graduação em Engenharia Mecânica.

Modo de acesso: Internet.

Disponível em: <http://doi.org/10.14393/ufu.te.2024.721>

Inclui bibliografia.

Inclui ilustrações.

1. Engenharia mecânica. I. Bandarra Filho, Enio Pedone
,1970-, (Orient.). II. Safaei, Mohammad Reza,1984-,
(Coorient.). III. Universidade Federal de Uberlândia.
Pós-graduação em Engenharia Mecânica. IV. Título.

CDU: 621

Bibliotecários responsáveis pela estrutura de acordo com o AACR2:

Gizele Cristine Nunes do Couto - CRB6/2091
Nelson Marcos Ferreira - CRB6/307

**UNIVERSIDADE FEDERAL DE UBERLÂNDIA**

Coordenação do Programa de Pós-Graduação em Engenharia Mecânica
Av. João Naves de Ávila, nº 2121, Bloco 1M, Sala 212 - Bairro Santa Mônica, Uberlândia-MG, CEP 38400-902
Telefone: (34) 3239-4282 - www.posmecanicaufu.com.br - secposmec@mecanica.ufu.br

**ATA DE DEFESA - PÓS-GRADUAÇÃO**

Programa de Pós-Graduação em:	Engenharia Mecânica				
Defesa de:	Tese de Doutorado, número 389, PPGEM				
Data:	30/10/2024	Hora de início:	14:00	Hora de encerramento:	15:40
Matrícula do Discente:	12013EMC004				
Nome do Discente:	Felipe Silva dos Santos				
Título do Trabalho:	An experimental study on heat transfer of nanoluid flowing in sudden expansion or contraction				
Área de concentração:	Transferência de Calor de Mecânica dos Fluidos				
Linha de pesquisa:	Geração e Conservação de Energia				
Projeto de Pesquisa de vinculação:	-				

Reuniu-se no por videoconferência, a Banca Examinadora, designada pelo Colegiado do Programa de Pós-graduação em Engenharia Mecânica, assim composta: Prof. Dr. Francisco José de Souza - FEMEC - UFU; João Marcelo Vedovotto - FEMEC - UFU; Prof. Dr. Muhammad Amjad - Technische Universität München - TUM; Prof. Dr. Muhammad Farooq - Prince Mohammad Bin Fahd University - PMU; Prof. Dr. Mohammad Reza Safaei - Clarkson University e Prof. Dr. Enio Pedone Bandarra Filho, orientador(a) do(a) candidato(a).

Iniciando os trabalhos o(a) presidente da mesa, Dr(a). Enio Pedone Bandarra Filho, apresentou a Comissão Examinadora e o candidato(a), agradeceu a presença do público, e concedeu ao Discente a palavra para a exposição do seu trabalho. A duração da apresentação do Discente e o tempo de arguição e resposta foram conforme as normas do Programa.

A seguir o senhor(a) presidente concedeu a palavra, pela ordem sucessivamente, aos(às) examinadores(as), que passaram a arguir o(a) candidato(a). Ultimada a arguição, que se desenvolveu dentro dos termos regimentais, a Banca, em sessão secreta, atribuiu o resultado final, considerando o(a) candidato(a):

Aprovado(a).

Esta defesa faz parte dos requisitos necessários à obtenção do título de Doutor.

O competente diploma será expedido após cumprimento dos demais requisitos, conforme as normas do Programa, a legislação pertinente e a regulamentação interna da UFU.

Nada mais havendo a tratar foram encerrados os trabalhos. Foi lavrada a presente ata que após lida e achada conforme foi assinada pela Banca Examinadora.



Documento assinado eletronicamente por **Enio Pedone Bandarra Filho, Professor(a) do Magistério Superior**, em 30/10/2024, às 15:39, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



Documento assinado eletronicamente por **João Marcelo Vedovotto, Professor(a) do Magistério Superior**, em 30/10/2024, às 15:40, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



Documento assinado eletronicamente por **Francisco José de Souza, Professor(a) do Magistério Superior**, em 30/10/2024, às 15:40, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



Documento assinado eletronicamente por **Muhammad Amjad, Usuário Externo**, em 30/10/2024, às 15:41, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



Documento assinado eletronicamente por **Mohammad Reza Safaei, Usuário Externo**, em 30/10/2024, às 15:43, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



Documento assinado eletronicamente por **Muhammad Farooq, Usuário Externo**, em 04/11/2024, às 15:25, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



A autenticidade deste documento pode ser conferida no site https://www.sei.ufu.br/sei/controlador_externo.php?acao=documento_conferir&id_orgao_acesso_externo=0, informando o código verificador **5725088** e o código CRC **5F560D1B**.

DEDICATION

*To my family for always encourage and
support me.*

ACKNOWLEDGEMENTS

I would like to express my gratitude to the Coordination for the Improvement of Higher Education Personnel (CAPES) and the National Council for Scientific and Technological Development (CNPq) for the financial support provided through the scholarship.

I also extend my thanks to the Federal University of Uberlândia, particularly the Graduate Program in Mechanical Engineering, to the Technical University of Munich (TUM) for their hospitality during my research stay in Germany. To the *Laboratório de Filmes Finos Processos de Plasma* at *Instituto de Ciências Tecnológicas e Exatas* of *Universidade Federal do Triângulo Mineiro* (UFTM) in the figure of Professor Dr. Rogério Valentim Gelamo and to GERDAU for supplying the graphene used in this research.

Special thanks to Professor Enio Pedone Bandarra Filho for his guidance during my Ph.D., to Professor Mohammad Reza Safaei for accepting to be my co-advisor during the Ph.D., and to Professors Muhammad Amjad and Dongsheng Wen for their hospitality during my time at TUM.

I am also grateful to the colleagues I met during my Ph.D. and to my family for the support I received.

SANTOS.F.S., **An experimental study on heat transfer of nanofluid flowing in sudden expansion or contraction**. 2024. 236p. PhD Thesis, Federal University of Uberlândia.

ABSTRACT

The control of thermal performance in energy supply systems is critical due to the increasing energy cost in the world. Many investigations of the impact of heat transfer due to nanofluids have been performed to determine the thermal enhancement in various engineering demands, among others. This experimental investigation deals with the behavior of the flow of nanofluid as heat transfer fluid, focusing on heat transfer phenomena and thermohydraulic performance inside horizontal tubes with sudden expansion or contraction. Small fractions of multi-walled carbon nanotubes (MWCNTs), functionalized multi-walled carbon nanotubes (FMWCNTs), and graphene nanoparticles were dispersed in a mixture of water and ethylene glycol with a 50:50 % in weight. These colloidal suspensions flowed inside a closed conduit towards a test section with an internal diameter of 14.29 mm (5/8-inch) and a length of 1700 mm. Four different cases were approached, in the first case the nanofluid flow inside a 5/8-inch copper pipe before entering in the test section. The second and third cases the nanofluid flow, before entering in the test section, inside a pipe with internal diameter of 20.64 mm (a commercial 7/8-inch copper pipe), and 26.99 mm (a commercial 9/8-inch copper pipe) respectively. In the fourth case, before entering in the test section, the nanofluid flow inside a heated pipe with 7.94 mm internal diameter (a commercial 3/8-inch copper pipe). The employed mass flow rate range varied from 9.33 g/s to 157.4 g/s, with two different inlet temperatures 25 °C and 45 °C, the mass concentrations used in the present study were of 0.005 % wt., 0.01 % wt. and 0.05 % wt., for three heat flux of 5 kW/m², 10 kW/m² and 12 kW/m². The results showed that the Reynolds number and the nanoparticles' mass concentration significantly affect the cooling fluid's heat transfer coefficient. In all tests analyzed, the heat transfer coefficient increased due to adding the nanoparticle and the Reynolds number. For Re = 5004, $q'' = 10 \text{ kW/m}^2$ and $\phi = 0.01\% \text{ wt.}$, the increases in heat transfer for MWCNT, FMWCNT, and graphene nanofluids for the first case were on average 7.29 %, 20.44 %, and 17.85 %, respectively. For lower concentrations ($\phi = 0.005\% \text{ wt.}$) and the same Re, the enhancements were on average 5.13 %, 14.48 %, and 17.44 %, respectively. Finally, for a constant Reynolds number, an increase in heat flux had no significant influence on heat transfer and thermohydraulic performance.

Keywords: Sudden expansion or contraction, Carbon nanotube, Graphene, Heat transfer, Thermohydraulic performance.

SANTOS.F.S., **Estudo experimental da transferência de calor no escoamento de nanofluidos em expansão ou contração súbita**. 2024. 236p. Tese de Doutorado, Universidade Federal de Uberlândia.

RESUMO

O controle do desempenho térmico em sistemas de fornecimento de energia é crucial devido ao aumento do custo da energia no mundo. Diversos trabalhos investigaram o impacto dos nanofluidos na transferência de calor, visando aprimorar a performance térmica em diversas aplicações de engenharia. A presente investigação experimental analisa o comportamento de nanofluidos como fluidos de troca térmica, com foco nos fenômenos de transferência de calor e no desempenho termohidráulico em tubos horizontais com expansão ou contração súbita. Pequenas concentrações em massa de nanotubos de carbono de paredes múltiplas (MWCNTs), nanotubos de carbono de paredes múltiplas funcionalizados (FMWCNTs) e nanopartículas de grafeno foram dispersas em uma mistura de água e etileno glicol com 50:50 % em massa. Essas suspensões coloidais escoaram dentro de um duto fechado em direção a uma seção de teste com diâmetro interno de 14,29 mm (5/8 da polegada) e comprimento de 1700 mm. Quatro casos diferentes foram investigados. No primeiro caso, o escoamento dos nanofluidos ocorreu dentro de um tubo de cobre de 5/8 da polegada antes de entrar na seção de teste. Nos segundo e terceiro casos o escoamento ocorreu antes de entrar na seção de teste, dentro de um tubo com diâmetro interno de 20,64 mm (um tubo de cobre comercial de 7/8 da polegada) e 26,99 mm (um tubo de cobre comercial de 9/8 da polegada), respectivamente. No quarto caso, antes de entrar na seção de teste, o escoamento dos nanofluidos ocorreu dentro de um tubo aquecido com diâmetro interno de 7,94 mm (um tubo de cobre comercial de 3/8 da polegada). A faixa de vazão mássica empregada variou de 9,34 g/s a 157,4 g/s, com duas temperaturas de entrada diferentes: 25 °C e 45 °C. As concentrações em massa usadas no presente trabalho foram de 0,005 % wt., 0,01 % wt. e 0,05 % wt., para três fluxos de calor de 5 kW/m², 10 kW/m² e 12 kW/m². Os resultados mostraram que o número de Reynolds e a concentração em massa das nanopartículas afetam significativamente a performance térmica do fluido de resfriamento. Em todos os testes analisados, o coeficiente de transferência de calor aumentou devido à adição da nanopartícula e ao aumento do número de Reynolds. Por exemplo, para $Re = 5004$, $q'' = 10 \text{ kW/m}^2$ e $\phi = 0,01\% \text{ wt.}$, os aumentos na taxa de transferência calor para os nanofluidos de MWCNT, FMWCNT e grafeno no primeiro caso foram em média 7,29 %, 20,44 % e 17,85 %, respectivamente. Para concentrações mais baixas ($\phi = 0,005\% \text{ wt.}$) e o mesmo Re , os aumentos foram em média 5,13 %, 14,48 % e 17,44 %, respectivamente. Finalmente, para um número de Reynolds constante, um aumento no fluxo de calor não teve influência significativa na performance térmica e no desempenho termohidráulico.

LIST OF FIGURES

Figure 1.1 – Flow separation patterns in widely used geometries. Adapted from (TOGUN ABDULLAH, 2015).....	2
Figure 2.1 – Variations surface temperature with different Reynolds numbers. Source: (ABDULRAZZAQ et al., 2020a).....	7
Figure 2.2 – (a) Schematic representation of the influence of CR on the fully developed Colburn j-factor as a function of Reynolds number for a square edge inlet (blue) and for reentrance (green). (b) Schematic diagram of the flow pattern for square edge inlets with different CR. Source: (BASHIR et al., 2019).....	8
Figure 2.3 – Number of papers published with heat transfer, nanofluids, expansion and contraction as keywords published. Source: (www.sciencedirect.com)	10
Figure 2.4 – Segregation of Nano-fluids depending on the dispersion of various nanoparticles in base fluids. Source: (AWAIS et al., 2020).	12
Figure 2.5 – Preparation process of nanofluids: (a)one-step method, (b) two-step method, and (c) SEM images of Al_2O_3 nanoparticles and CNTs nanoparticles , TEM images of ZnO nanoparticles and Fe_3O_4 nanoparticles. Source: (WANG et al., 2023)	14
Figure 2.6 – Classification of surfactants based on head composition. Source: (YANG et al., 2020).....	15
Figure 2.7 – Most used methods for measuring and improving the stability of nanofluids. Source: (YANG et al., 2020).	31
Figure 2.8 – (a) Van der Waals force and electrostatic repulsion and electrostatic stability and steric stability. (b) Brownian motion of the nanofluid, and the schematic diagram of the boundary layer and the aggregation effect. Adapted from: (CHU et al., 2023)	32

Figure 2.9 – (a) Idealized course of boundary streamlines and (b) pressure profile for a sudden expansion. Source: (ROUL and DASH, 2011).....	36
Figure 2.10 – (a) Idealized course of boundary streamlines and (b) pressure profile for a sudden contraction. Source: (ROUL and DASH, 2011).....	37
Figure 2.11 – Schematic diagram of the calculation of the flow area with triple descent (BFS). Source: (QI et al., 2020)	42
Figure 2.12 – Schematic diagram of the experimental apparatus used by (TOGUN; KAZI; BADARUDIN, 2017).....	44
Figure 2.13 – (a) Schematic representation of the experimental apparatus, (b) configuration of the tested channel used by (HILO et al., 2020)	46
Figure 2.14 – Schematic diagram of the test section used by (MONTAZER et al., 2020b)....	46
Figure 2.15 – MBFS schematic diagram and experimental setup used by (ABU TALIB; SALMAN, 2023).....	47
Figure 2.16 – Schematical configuration analyzed, with heat flux range of W/m^2 to $10000 W/m^2$. Source: (SAFAEI et al., 2014)	54
Figure 3.1 – Nanofluid production process. Source: Author's own.....	67
Figure 3.2 – Nanofluid synthesis process. Source: Author's own.....	69
Figure 3.3 – Functionalization process for MWCNT. Source: Author's own.....	70
Figure 3.4 – Nanofluids samples (1 - MWCNT; 2 - FMWCNT; 3 - Graphene and 4 - Industrial Graphene) in the highest mass concentration and base fluid (5 - H ₂ O: EG 50:50 % wt.). Source: Author's own.....	70
Figure 3.5 – TEM images for (a) MWCNT; (b) FMWCNT; (c) Graphene and (d) Industrial graphene. Source: Author's own.....	71
Figure 3.6 – SEM images for (a) MWCNT; (b) FMWCNT; (c) Graphene and (d) Industrial graphene. Source: Author's own.....	72

Figure 3.7 – UV – VIS spectrophotometer routine. Source: Author's own.....	73
Figure 3.8 – Thermal conductivity meter LINSEIS and THB – 1 sensor. Source: Author's own.....	75
Figure 3.9 – Experimental setup for thermal conductivity measurement. Source: Author's own.....	76
Figure 3.10 – Viscometer Stabinger TM SVM TM 3000, from Anton Paar. Source: (CONTRERAS et al., 2019).....	77
Figure 3.11 – Test bench for measuring nanofluid flow and heat transfer. 1: Test section; 2: Differential pressure transmitter; 3: Pressure transmitter; 4: Nylon supports; 5: flow meter; 6: Preheating system; 7: Heat exchanger; 8: Water chiller; 9: Nanofluid reservoir; 10: Temperature transmitter; 11: Water pump; 12: Condensing unit; 13: Water pump; 14: Gear pump; 15: Electric motor; 16: Data Acquisition (NI-DAQ); 17: Computer. Source: Author's own.....	79
Figure 3.12 – Cross – section of test section during nanofluid flow. (a) CR = 1.4; (b) CR = 1.9; (c) ER = 1.9 and (d) Picture of geometry change parts (1 - Flange with 3/8 - inch; 2 - Flange with 7/8 - inch; Flange with 9/8 - inch; 4 - Flange attached at test section with 5/8 – inch and O - Ring seal). Source: Author's own.....	80
Figure 3.13 – Schematic representation of (a) T-type thermocouples attached to the test section; (b) installation position of the thermocouples in the test section; (c) front view of the flange used to attach the test section to the expansion/contraction section. Source: Author's own.....	82
Figure 3.14 – Constructive details of test section. (a) Test section covered with Kapton flexible heaters; (b) Test section covered with Fiberglass heaters. Source: Author's own.....	82
Figure 3.15 – (a) Variac of 10 kVA. (b) Linear current sensor. (c) RTD type PT100. (d) Glass wool insulation covering the test section. (e) Elastomeric foam covering the test section. (f) Nylon bushed at inlet of the test section. Source author's own.....	83
Figure 3.16 – (a) Structural diagram of the installation of measuring instruments in the test section. (b) Insulated test section. Source: Author's own.....	84
Figure 3.17 – Cooling system schematical representation. Source: Author's own.....	85

Figure 3.18 – Preheating system representation. Source: Author’s own.....	86
Figure 3.19 – Static power converter TH6200A16. Source: Author’s own.....	87
Figure 3.20 – (a) Water pump with magnetic coupling. (b) Air eliminator valve. (c) Coriolis – type mass flow meter. Source: Author’s own.....	88
Figure 3.21 – LabView® interface program. Source: Author’s own.....	89
Figure 3.22 – NI cDAQ-9178 modular system used in the data acquisition system. Source: Author’s own.....	89
Figure 3.23 – Electrical panels. (a) Data acquisition panel. (b) Power panel. Source: Author’s own.....	91
Figure 3.24 – Experimental setup. Source: Author’s own.....	91
Figure 3.25 – Experimental results for the mixture of water and ethylene glycol relating the electrical power, $\dot{Q}_{E.B.}$, to the power calculated by the energy balance, $\dot{Q}_{E.P.}$ for: (a) CR = 1.4 and $T_{in} = 25\text{ }^{\circ}\text{C}$. (b) CR = 1.4 and $T_{in} = 45\text{ }^{\circ}\text{C}$. (c) CR = 1.9 and $T_{in} = 25\text{ }^{\circ}\text{C}$. (d) CR = 1.9 and $T_{in} = 45\text{ }^{\circ}\text{C}$. (e) ER = 1.7 and $T_{in} = 25\text{ }^{\circ}\text{C}$. (f) ER = 1.7 and $T_{in} = 45\text{ }^{\circ}\text{C}$. Source: Author’s own.....	95
Figure 3.26 – Experimental friction factor versus Reynolds number. Comparison with the Blasius model for turbulent flow and laminar regime for: (a) CR = 1.4 and (b) CR = 1.9. Source: Author’s own.....	97
Figure 3.27 – Experimental friction factor versus Reynolds number. Comparison with the Blasius model for turbulent flow and laminar regime for the expansion ratio case (ER = 1.7). Source: Author’s own.....	97
Figure 3.28 – Comparison between the experimental Nu and the correlation of Sieder & Tate for: (a) CR = 1.4 and (b) CR = 1.9. Source: Author’s own.....	100
Figure 3.29 – Comparison between the experimental Nu and the correlation of Sieder & Tate for ER = 1.7. Source: Author’s own.....	100

Figure 3.30 – Comparison between the experimental Nu and the Gnielinski model for $ER = 1.7$. Source: Author's own.....	101
Figure 3.31 – Comparison between the experimental Nu and the Gnielinski model for $ER = 1.7$. Source: Author's own.....	101
Figure 4.1 – Nanofluids samples separate for visual stability inspection. (a) Carbon nanotubes, (b) Graphene. Source: Author's own.....	104
Figure 4.2 – Absorbance versus wavelength for (a) MWCNT/H ₂ O-EG and (c) FMWCNT/H ₂ O-EG samples, and concentration over time for (b) MWCNT/H ₂ O-EG and (d) FMWCNT/H ₂ O-EG nanofluids. Source: Author's own.....	105
Figure 4.3 – Absorbance versus wavelength for (a) Graphene/H ₂ O-EG and (c) Industrial graphene/H ₂ O-EG samples, and concentration over time for (b) Graphene/H ₂ O-EG and (d) Industrial graphene /H ₂ O-EG nanofluids. Source: Author's own.....	106
Figure 4.4 – Experimental results for Thermal conductivity of nanofluid samples and base fluid. (a) MWCNT/H ₂ O:EG. (b) FMWCNT/H ₂ O:EG. Source: Author's own.....	108
Figure 4.5 – Experimental results for Thermal conductivity of nanofluid samples and base fluid. (a) Graphene/H ₂ O:EG. (b) Industrial graphene/H ₂ O:EG. Source: Author's own.....	109
Figure 4.6 – Experimental results for dynamic viscosity of nanofluid samples and base fluid. (a) MWCNT/H ₂ O:EG. (b) FMWCNT/H ₂ O:EG. (c) Graphene/H ₂ O:EG. (d) Industrial graphene/H ₂ O:EG. Source: Author's own.....	112
Figure 4.7 – Relative viscosity of nanofluids samples of: (a) Carbon nanotubes. (b) Graphene. Source: Author's own.....	113
Figure 4.8 – Experimental for density of nanofluid samples and base fluid. (a) MWCNT/H ₂ O:EG. (b) FMWCNT/H ₂ O:EG. (c) Graphene/H ₂ O:EG. (d) Industrial graphene/ H ₂ O:EG. Author's own.....	116
Figure 4.9 – Specific heat with different nanoparticles factions in base fluid for: (a) MWCNT/H ₂ O-EG. (b) Graphene/H ₂ O-EG.....	117

- Figure 4.10 – Convective heat transfer and Nusselt number MWCNT nanofluid samples. (a) MWCNT ($h \times \dot{m}$). (b) MWCNT ($Nu \times Re$). Source: Author's own.....120
- Figure 4.11 – Convective heat transfer and Nusselt number of FMWCNT nanofluid samples. (a) FMWCNT ($h \times \dot{m}$). (b) FMWCNT ($Nu \times Re$). Source: Author's own.....121
- Figure 4.12 – Convective heat transfer and Nusselt number of graphene nanofluid samples. (a) Graphene ($h \times \dot{m}$). (b) Graphene ($Nu \times Re$). Source: Author's own.....121
- Figure 4.13 – Local Nusselt number for the nanofluids samples along the test section. (a) $\dot{m} = 15.74 \text{ g/s}$ and $T_{in} = 25 \text{ }^{\circ}\text{C}$. (b) $\dot{m} = 15.74 \text{ g/s}$ and $T_{in} = 45 \text{ }^{\circ}\text{C}$. (c) $\dot{m} = 157.4 \text{ g/s}$ and $T_{in} = 25 \text{ }^{\circ}\text{C}$. (d) $\dot{m} = 157.4 \text{ g/s}$ and $T_{in} = 45 \text{ }^{\circ}\text{C}$. Source: Author's own.....122
- Figure 4.14 – Convective heat transfer and Nusselt number MWCNT nanofluid samples with $T_{in} = 25 \text{ }^{\circ}\text{C}$ and $q'' = 10 \text{ kW/m}^2$ for: (a) MWCNT ($h \times \dot{m}$) and $CR = 1.4$; (b) MWCNT ($Nu \times Re$) and $CR = 1.4$. Source Author's own.....125
- Figure 4.15 – Convective heat transfer and Nusselt number MWCNT nanofluid samples with $T_{in} = 25 \text{ }^{\circ}\text{C}$ and $q'' = 10 \text{ kW/m}^2$ for: (a) MWCNT ($h \times \dot{m}$) and $CR = 1.4$; (b) MWCNT ($Nu \times Re$) and $CR = 1.4$. Source Author's own.....125
- Figure 4.16 – Convective heat transfer for FMWCNT nanofluid samples at different contraction ratios. (a) $T_{in} = 25 \text{ }^{\circ}\text{C}$ and $0.005 \text{ } \%$ wt. (b) $T_{in} = 45 \text{ }^{\circ}\text{C}$ and $0.005 \text{ } \%$ wt. Source: Author's own.....126
- Figure 4.17 – Convective heat transfer for FMWCNT nanofluid samples at different contraction ratios. (a) $T_{in} = 25 \text{ }^{\circ}\text{C}$ and $0.01 \text{ } \%$ wt. (b) $T_{in} = 45 \text{ }^{\circ}\text{C}$ and $0.01 \text{ } \%$ wt. Source: Author's own.....127
- Figure 4.18 – Local Nusselt number along the axial position for: (a) $\dot{m} = 0.0157 \text{ kg/s}$; (b) $\dot{m} = 0.157 \text{ kg/s}$. Relative Nusselt number along the axial position for: (c) $\dot{m} = 0.0157 \text{ kg/s}$; (d) $\dot{m} = 0.157 \text{ kg/s}$. Source: Author's own.....128
- Figure 4.19 – Convective heat transfer for MWCNT nanofluid samples. (a) $T_{in} = 25 \text{ }^{\circ}\text{C}$ (b) $T_{in} = 45 \text{ }^{\circ}\text{C}$. Source: Author's own.....130

Figure 4.20 – Convective heat transfer for FMWCNT nanofluid samples. (a) $T_{in} = 25\text{ }^{\circ}\text{C}$ (b) $T_{in} = 45\text{ }^{\circ}\text{C}$. Source: Author's own.....	131
Figure 4.21 – Convective heat transfer for Industrial graphene nanofluid samples. (a) $T_{in} = 25\text{ }^{\circ}\text{C}$ (b) $T_{in} = 45\text{ }^{\circ}\text{C}$. Source: Author's own.....	131
Figure 4.22 – Nusselt number for MWCNT nanofluid samples. (a) $T_{in} = 25\text{ }^{\circ}\text{C}$ (b) $T_{in} = 45\text{ }^{\circ}\text{C}$. Source: Author's own.....	132
Figure 4.23 – Nusselt number for FMWCNT nanofluid samples. (a) $T_{in} = 25\text{ }^{\circ}\text{C}$ (b) $T_{in} = 45\text{ }^{\circ}\text{C}$. Source: Author's own.....	133
Figure 4.24 – Nusselt number for Industrial graphene nanofluid samples. (a) $T_{in} = 25\text{ }^{\circ}\text{C}$ (b) $T_{in} = 45\text{ }^{\circ}\text{C}$. Source: Author's own.....	133
Figure 4.25 – Pressure loss and friction factor for MWCNT nanofluid samples. (a) MWCNT ($\Delta P \times \dot{m}$). (b) MWCNT ($f \times Re$). Source: Author's own.....	135
Figure 4.26 – Pressure loss and friction factor for FMWCNT nanofluid samples. (a) FMWCNT ($\Delta P \times \dot{m}$). (b) FMWCNT ($f \times Re$). Source: Author's own.....	135
Figure 4.27 – Pressure loss and friction factor for graphene nanofluid samples. (a) Graphene ($\Delta P \times \dot{m}$). (b) Graphene ($f \times Re$). Source: Author's own.....	136
Figure 4.28 – Pressure loss and friction factor for MWCNT nanofluid samples at CR = 1.4. (a) MWCNT ($\Delta P \times \dot{m}$). (b) MWCNT ($f \times Re$). CR = 1.9. (c) MWCNT ($\Delta P \times \dot{m}$). (d) MWCNT ($f \times Re$). Source: Author's own.....	137
Figure 4.29 – Pressure loss and friction factor for FMWCNT nanofluid samples at CR = 1.4. (a) FMWCNT ($\Delta P \times \dot{m}$). (b) FMWCNT ($f \times Re$). CR = 1.9. (c) FMWCNT ($\Delta P \times \dot{m}$). (d) FMWCNT ($f \times Re$). Source: Author's own.....	138
Figure 4.30 – Pressure loss and friction factor for Graphene nanofluid samples at CR = 1.4. (a) Graphene ($\Delta P \times \dot{m}$). (b) Graphene ($f \times Re$). CR = 1.9. (c) Graphene ($\Delta P \times \dot{m}$). (d) Graphene ($f \times Re$). Source: Author's own.....	139

Figure 4.31 – Pressure loss and friction factor for MWCNT nanofluid samples flowing under expansion ($ER = 1.7$). (a) MWCNT ($\Delta P \times \dot{m}$). (b) MWCNT ($f \times Re$). Source: Author's own.....	141
Figure 4.32 – Pressure loss and friction factor for FMWCNT nanofluid samples flowing under expansion ($ER = 1.7$). (a) FMWCNT ($\Delta P \times \dot{m}$). (b) FMWCNT ($f \times Re$). Source: Author's own.....	141
Figure 4.33 – Pressure loss and friction factor for industrial graphene nanofluid samples flowing under expansion ($ER = 1.7$). (a) Industrial graphene ($\Delta P \times \dot{m}$). (b) Industrial graphene ($f \times Re$). Source: Author's own.....	142
Figure 4.34 – Experimental results of the thermohydraulic performance for the straight pipe case of samples with (a) 0.005 % wt. and (b) 0.01 % wt. Source: Author's own.....	143
Figure 4.35 – Thermal - hydraulic performance results of samples for $CR = 1.4$ with: (a) 0.005 % wt. and (b) 0.01 % wt. For $CR = 1.9$. (c) 0.005 % wt. and (d) 0.01 % wt. Source: Author's own.....	145
Figure 4.36 – Thermal - hydraulic performance results of nanofluid samples for $ER = 1.7$ with: (a) 0.005 % wt. and (b) 0.01 % wt. Source: Author's own.....	147
Figure 4.37 – Comparison of experimental data with the proposed mathematical model for thermal conductivity. (a) MWCNT ($\kappa \times \phi$). (b) MWCNT ($\kappa_{exp} \times \kappa_{model}$). Source: Author's own.....	149
Figure 4.38 – Comparison of experimental data with the proposed mathematical model for thermal conductivity. (a) FMWCNT ($\kappa \times \phi$). (b) FMWCNT ($\kappa_{exp} \times \kappa_{model}$). Source: Author's own.....	149
Figure 4.39 – Comparison of experimental data with the proposed mathematical model for thermal conductivity. (a) Graphene ($\kappa \times \phi$). (b) Graphene ($\kappa_{exp} \times \kappa_{model}$). Source: Author's own.....	150
Figure 4.40 – Comparison of experimental data with the proposed mathematical model for thermal conductivity. (a) Industrial graphene ($\kappa \times \phi$). (b) Industrial graphene ($\kappa_{exp} \times \kappa_{model}$). Source: Author's own.....	150

Figure 4.41 – Comparison of experimental data with the proposed mathematical model for dynamic viscosity. (a) MWCNT ($\mu \times \phi$). (b) MWCNT ($\mu_{exp} \times \mu_{model}$). Source: Author's own.....	151
Figure 4.42 – Comparison of experimental data with the proposed mathematical model for dynamic viscosity. (a) FMWCNT ($\mu \times \phi$). (b) FMWCNT ($\mu_{exp} \times \mu_{model}$). Source: Author's own.....	152
Figure 4.43 – Comparison of experimental data with the proposed mathematical model for dynamic viscosity. (a) Graphene ($\mu \times \phi$). (b) Graphene ($\mu_{exp} \times \mu_{model}$). Source: Author's own.....	152
Figure 4.44 – Comparison of experimental data with the proposed mathematical model for dynamic viscosity. (a) Industrial graphene ($\mu \times \phi$). (b) Industrial graphene ($\mu_{exp} \times \mu_{model}$). Source: Author's own.....	153
Figure 4.45 – Comparison between the experimental convective heat transfer coefficient and Gnielinski's correlation. (a) MWCNT. (b) FMWCNT. (c) Graphene. Source: Author's own.....	156
Figure 4.46 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for MWCNT nanofluid samples. (a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.....	157
Figure 4.47 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for FMWCNT nanofluid samples. (a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.....	158
Figure 4.48 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for graphene nanofluid samples. (a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.....	158
Figure 4.49 – Comparison between the experimental convective heat transfer coefficient and Gnielinski's correlation for nanofluid flowing under expansion. (a) MWCNT. (b) FMWCNT. (c) Industrial graphene. Source: Author's own.....	161

Figure 4.50 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for MWCNT nanofluid samples.

(a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.....162

Figure 4.51 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for FMWCNT nanofluid samples. (a)

$Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own..... 163

Figure 4.52 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for Industrial graphene nanofluid samples. (a)

$Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.....163

Figure 4.53 – Colburn heat transfer factor j versus Reynolds, Re number for turbulent flow of base fluid (H2O-EG 50:50 % wt.) under contraction. (a) CR = 1.4. (b) CR = 1.9. Source:

Author's own.....165

Figure 4.54 – Correlation for CR = 1.4. (a) MWCNT. (b) FMWCNT. (c) Graphene. Source: Author's own.....168

Figure 4.55 – Correlation for CR = 1.9. (a) MWCNT. (b) FMWCNT. (c) Graphene. Source: Author's own.....170

LIST OF TABLES

Table 2.1 – Thermal conductivity of some materials, base fluids and nanofluids.....	13
Table 2.2 – Regression models for specific heat of some metal-oxide based nanofluids.....	23
Table 2.3 – Some experimental setup details of nanofluid flow through sudden geometry change in recent literature.....	33
Table 2.4 – Summary of the state-of-the-art involving heat transfer in nanofluid flow under expansion.....	48
Table 2.5 – Summary of the state-of-the-art involving heat transfer in nanofluid flow under contraction.....	57
Table 2.6 – Correlations for heat transfer of nanofluids in sudden geometry change.....	60
Table 2.7 – Head loss correlations for heat transfer of nanofluids/work fluid in sudden geometry change.....	62
Table 3.1 – Thermophysical properties of nanoparticles and base fluids.....	67
Table 3.2 – Description of nanofluid samples used in the present work.....	68
Table 3.3 – Specifications of THB – 1 LINSEIS provided by manufacturer.....	75
Table 3.4 – Uncertainty data of Anton Paar viscometer measurement provided by the manufacturer.....	77
Table 3.4 - Modules and instruments that integrate the monitoring system.....	89
Table 3.5 – Conditions for the tests with water-ethylene glycol mixture (H ₂ O:EG 50:50 wt.%).....	92
Table 3.6 – Uncertainties of primary and secondary parameters or calculated measurement-dependent variables.....	102
Table 4.1 – Operational parameters for tests in the straight pipe.....	119

Table 4.2 – Operational parameters for tests of nanofluid flowing under contraction.....	124
Table 4.3 – Operational parameters for tests of nanofluid flowing under expansion.....	129
Table 4.4– Thermal conductivity model constants for nanofluid samples based on (H ₂ O-EG/50:50 % wt.).....	148
Table 4.5 – Dynamic viscosity model constants for nanofluid samples based on (H ₂ O-EG/50:50 % wt.).....	151
Table 4.6 – Average deviation of experimental data and Gnielinski's model (1975).....	154
Table 4.7 – Parameters of correlations for the straight pipe case in turbulent flow.....	157
Table 4.8 – Average deviation of experimental data in the turbulent regime and the model described in Eq. 4.6.....	157
Table 4.9 – Average deviation of experimental data and Gnielinski's model (1975).....	160
Table 4.10 – Parameters of correlations for the nanofluid flowing under expansion.....	162
Table 4.11 – Average deviation of experimental data and Gnielinski's model (1975).....	162
Table 4.12 – Correlation models for geometry investigated.....	166
Table 4.13 – Parameters of correlations.....	166

NOMENCLATURE

Latin letters

A	- Relative absorbance
A_0	- Initial absorbance
C	- Relative concentration
C_0	- Initial concentration
C_p	- Specific heat at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$)
d	- Pipe diameter (mm)
e	- Thickness (mm)
E	- Error
f	- Friction factor
H	- High of pipe (m)
h	- Heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
I	- Current (A)
k_b	- Boltzman constant (J K^{-1})
L	- Length of control volume (m)
$\frac{L}{H}$	- Relative axial position of the control volume in the straight pipe
$\ln$	- Natural logarithm
m	- Mass
$\dot{m}$	- Mass flow rate (g s^{-1})
Nu	- Nusselt number
n	- Temperature measuring point number
P	- Pressure (Pa)
p	- Perimeter of the pipe (mm)
Pr	- Prandtl number
$\dot{Q}_{\text{conv}}$	- Convective heat (W m^{-2})
$\dot{Q}_{\text{E.B.}}$	- Energy balance (W)
$\dot{Q}_{\text{E.P.}}$	- Power supply (W)

q''	- heat per unit area (W m^2)
R	- Thermal resistance ($\text{m}^2 \text{K W}^{-1}$)
r	- Aspect ratio
Re	- Reynolds number
T	- Temperature ($^{\circ}\text{C}$)
V	- Voltage (V)
W	- Water
$\dot{W}$	- Pumping power (W)
wt.	- Weight (kg)

Greek symbols

α	- Thermal diffusivity ($\text{m}^2 \text{s}^{-1}$)
ΔP	- Pressure drop (Pa)
ϕ	- Mass fraction of nanoparticles (%)
μ	- Dynamic viscosity (Pa s)
κ	- Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
ρ	- Density (g cm^{-3})

Subscripts

avg	- Average
bf	- Base fluid
D	- Hydraulic diameter (m)
in	- Inlet
nf	- Nanofluid
out	- Outlet
w	- Wall

Abbreviations

BFS	- Backward facing step
CNT	- Carbon nanotube

CR	- Contraction ratio
DBFS	- Double backward facing step
EES	- Engineering equation solver
E.B.	- Energy balance
EG	- Ethylene – glycol
EMT	- Effective medium theory
ER	- Expansion ratio
FFS	- Forward facing step
LESTnano	- Laboratório de Energia, Sistemas Térmicos e Nanotecnologia
MWCNT	- Multiwalled carbon nanotube
SEM	- Scanning electron microscope
TEM	- Transmission electron microscopy
THB	- Transient hot bridge
UFU	- Universidade Federal de Uberlândia
vol.	- Volume (m^3)

SUMMARY

LIST OF FIGURES	vii
LIST OF TABLES	xvii
NOMENCLATURE.....	xix
CHAPTER I.....	1
INTRODUCTION	1
Motivation.....	1
Objectives	3
Organization of the Thesis	4
CHAPTER II.....	5
LITERATURE REVIEW.....	5
2.1 Introduction.....	5
2.2 Nanofluids	10
<i>2.2.1 Preparation of nanofluids</i>	<i>13</i>
<i>2.2.2 Nanofluid Effective Properties.....</i>	<i>16</i>
<i>Thermal conductivity.....</i>	<i>16</i>
<i>Specific heat</i>	<i>22</i>
<i>Dynamic viscosity.....</i>	<i>26</i>
2.3 Flow geometry.....	34
<i>2.3.1 Balance equations and boundary conditions</i>	<i>34</i>
<i>2.3.2 Nanofluid flow under expansion</i>	<i>39</i>
<i>2.3.3 Nanofluid flow under contraction</i>	<i>54</i>
2.4 Conclusions	63

CHAPTER III	65
EXPERIMENTAL PROCEDURES	65
3.1 Synthesis of nanofluids	65
3.2 Stability analysis.....	71
3.3 Thermophysical properties.....	73
3.3.1 Thermal conductivity.....	73
3.3.2 Density and dynamic viscosity	75
3.3.3 Specific heat	77
3.4 Experimental setup	77
3.4.1 Test section.....	79
3.4.2 Cooling system	83
3.4.3 Preheating system	84
3.4.4 Flow system and mass flow measurement system	86
3.4.5 Monitoring and data acquisition system	87
3.5 Analysis and validation of the experimental setup	91
3.5.1 Energy balance and test section insulation.....	93
3.5.2 Pressure drop and friction factor.....	93
3.5.3 Heat transfer coefficient.....	97
3.6 Uncertainties Analysis	101
CHAPTER IV	103
RESULTS AND DISCUSSION	103
4.1 Stability analysis.....	103
4.2 Thermophysical properties.....	107
4.2.1 Thermal conductivity	108
4.2.2 Dynamic viscosity.....	110
4.2.3 Density	114
4.2.4 Specific heat	117

4.3 Heat transfer performance	118
4.3.1 <i>Convective heat transfer for straight pipe case</i>	119
4.3.2 <i>Convective heat transfer for nanofluid flowing under contraction.....</i>	123
4.3.3 <i>Convective heat transfer for nanofluid flowing under expansion</i>	129
4.4 Friction factor and pressure drop	134
4.4.1 <i>Nanofluid flowing in a straight pipe</i>	134
4.4.2 <i>Nanofluid flowing under contraction</i>	136
4.4.3 <i>Nanofluid flowing under expansion</i>	140
4.5 Thermohydraulic performance	142
4.5.1 <i>Nanofluid flowing in a straight pipe</i>	142
4.5.2 <i>Nanofluid flowing under contraction</i>	144
4.5.3 <i>Nanofluid flowing under expansion</i>	146
4.6 Mathematical models proposed for thermophysical properties	148
4.6.1 <i>Thermal conductivity model</i>	148
4.6.2 <i>Dynamic viscosity model</i>	150
4.7 Mathematical models proposed for convective heat transfer	153
4.7.1 <i>Heat transfer by convection in turbulent flow for the straight pipe case.....</i>	153
4.7.2 <i>Heat transfer by convection in turbulent regime for nanofluid flowing under expansion</i>	159
4.7.3 <i>Heat transfer by convection in turbulent regime for nanofluid flowing under contraction.....</i>	164
CHAPTER V	171
CONCLUSIONS	171
5.1 Final conclusions	171
5.2 Recommendations for future work	173
REFERENCES	175
APPENDIX A	217

APPENDIX B	219
APPENDIX C	221
APPENDIX D	223
APPENDIX E	225
APPENDIX F	227
APPENDIX G	231
APPENDIX H	232
APPENDIX I	233
APPENDIX J	234
APPENDIX K	235
APPENDIX L	236

CHAPTER I

INTRODUCTION

Motivation

The study of heat transfer and nanofluid flow in circular tubes using numerical and experimental approach are primarily investigated by many authors such as (AZIZIFAR et al, 2021; BRICLOT et al., 2023; ERDEM and VAROL, 2020; KHAJEH ARZANI et al, 2016; MENG et al, 2022; MOUSAVI et al., 2022; MURTHY et al, 2024; TEKIR et al, 2022; ZHANG et al, 2021). However fewer researchers have considered the effects of sudden contraction and/or expansion in heat transfer and pressure drop of nanofluid flow.

The use of annular passages in engineering application extends through such areas as heat exchangers, gas turbines, cooling of the nuclear reactor and some operation industries, cementing operations, formation fracturing, and flow of lubricants in journal bearing and pressure bushings, as well as those applications found in the form of horizontal or vertical directions (KAZI and TOGUN, 2015). Therefore, some researchers have studied fluid flow and heat transfer in horizontal and vertical directions for different types of fluid used in varied application like air, water, oil, and gas (BASHIR et al., 2019; FLOREZ MORALES et al., 2023; KEKLIKCIOGLU et al., 2019; SUN et al., 2020).

Flows through a sudden axisymmetric contraction or expansion, in forward facing step (FFS) or backward facing step (BFS) channels and through channels with obstacles, create separation and subsequent reattachment zones as seen in Fig. 1.1 (TOGUN ABDULLAH, 2015). Separation and recirculation zones have a significant impact on the performance of heat exchangers, electronic cooling systems, automotive radiators, microchannels, circular ducts,

and many other heat exchange equipment, which is taken into account in engineering projects. As a result, the reattachment zone mixes a considerable amount of low and high energy (SALMAN et al., 2020). Studies on heat transfer in nanofluid flow under sudden expansion and or contraction whether they are axisymmetric, in FFS or BFS channels are rather limited for the laminar regime, and most works related to the topic have been performed numerically. Much of the experimental research related to the topic so far has been done exclusively in the turbulent or transition regime (ABU TALIB et al., 2022; HILO et al., 2020; KHERBEET et al., 2015; MONTAZER et al., 2020a; TOGUN et al., 2017).

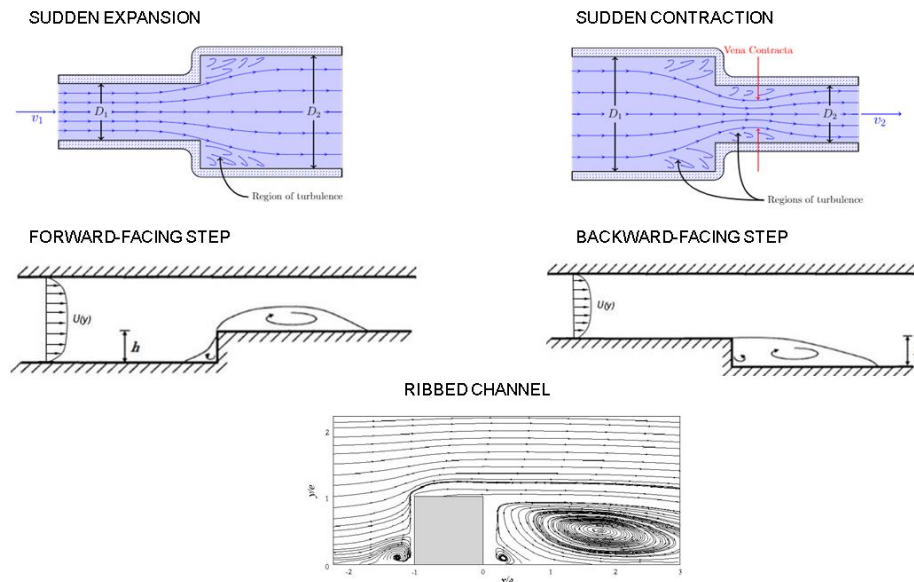


Figure 1.1 – Flow separation patterns in widely used geometries. Adapted from (TOGUN ABDULLAH, 2015).

This study investigated the thermohydraulic performance of MWCNT, FMWCNT, and graphene suspended in a base fluid composed of a mixture of water and ethylene glycol with a 50 % mass fraction of each substance (H_2O - EG 50:50 % wt.), flowing in a horizontal tube under turbulent and laminar regimes with a constant heat flux of 5 kW/m^2 , 10 kW/m^2 and 12 kW/m^2 for different nanoparticle mass concentrations ranging from 0.005 % to 0.05 %. Through a systematic approach, the influence of various parameters, including mass fraction, flow rate, and temperature, was investigated, providing a comprehensive analysis and discussion of their effects. Moreover, recognizing the substantial impact of the contraction ratio (CR) and expansion ratio (ER) on fluid flow and heat transfer, it was meticulously accounted for

throughout the study. With the experimental endeavors undertaken in this study, the aim was to contribute valuable empirical data that will not only enhance the understanding of nanofluid behavior but also improve the accuracy of predictive models in this domain.

Objectives

This thesis aims to evaluate, theoretically and experimentally, the thermohydraulic performance of nanofluids based on a mixture of water and ethylene glycol (H₂O - EG 50:50 % wt.) in different geometries and flow conditions. For this purpose, nanofluids containing graphene, multi-walled carbon nanotubes (MWCNT) and functionalized multi-walled carbon nanotubes (FMWCNT) in different concentrations were evaluated. An experimental setup, developed and modified at the *Laboratório de energia, sistemas térmicos e nanotecnologia* (LEST-Nano), was used to evaluate heat transfer and pressure drop in the system. As specific objectives were defined:

- Present an up-to-date state-of-the-art review of the application of nanofluids in horizontal pipes with a sudden change in geometry.
- Produce nanofluids with different concentrations of graphene nanoparticles, MWCNT and functionalized MWCNT using a mixture of water and ethylene glycol (H₂O - EG 50:50 % wt.) as the base fluid.
- Perform experimental measurements on the thermophysical properties of nanofluids, such as: thermal conductivity, dynamic viscosity, density, and specific heat.
- Evaluate the stability of the nanofluids using UV-VIS spectrophotometry and visual inspection methods.
- Evaluate the effects of the main physical parameters on heat transfer and pressure drop, such as: nanoparticle concentration, mass flow rate and nanofluid inlet temperature.
- Theoretical and experimental evaluation of thermohydraulic performance in the flow of nanofluids without phase change in closed conduits with contraction and expansion.
- Correlate the experimental results obtained with the literature to measure the gains or losses obtained for the parameters evaluated.

Organization of the Thesis

This thesis is sub-divided into five chapters, in which the topics covered in this study are presented step by step, in order to achieve the main objective. The chapters are organized as follows:

Chapter I contains the importance, motivation and objectives for this study. A brief introduction to nanofluid flow in different configurations and effects on heat transfer are also incorporated in this section.

Chapter II is related to the experimental and numerical studies covering turbulent and laminar flow through sudden expansion or contraction in pipes with constant wall heat flux. In addition, study of previous works and the relevant correlations of heat transfer performance and the variable parameters have presented.

Chapter III is representing the experimental setup, materials, nanofluids preparation process, morphological characterization, thermophysical properties, stability analysis of the nanofluids and the validation of the experimental setup. The last subsection of this chapter is dedicated to analyzing the uncertainties of the variables measured and calculated in the tests performed.

Chapter IV presents the experimental results obtained for the nanofluids. Initially, the thermophysical properties (thermal conductivity, dynamic viscosity, and density) are characterized as functions of temperature and nanoparticle concentration. The influence of physical parameters on the heat transfer rate and pressure drop is then evaluated, with particular attention to the effects of temperature, working fluid, mass flow rate, and nanoparticle concentration. A comparative analysis is also made between the experimental results obtained for the nanofluids and the base fluid, in order to identify whether or not there was an intensification of the heat transfer rate and an increase in the pressure drop. A further analysis is made regarding the thermohydraulic performance of the nanofluids after the tests have been performed on the experimental setup.

Chapter V discusses the main conclusions of this work and suggestions for future work.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Applications of nanofluids as heat transfer fluids to increase the performance of thermal systems have been widely investigated over the past 30 years by researchers worldwide. (CARDENAS CONTRERAS and BANDARRA FILHO, 2022; KUMAR et al., 2024; LI et al., 2020; LIN et al., 2023; MERCAN, 2022; VAKA and WALVEKAR, 2023). Numerous investigations have been carried out to achieve an increase in the thermal performance of nanofluids, depending on the configuration of the geometry in which the flow occurs and the purpose for which it is intended. Some numerical and experimental studies are dedicated to investigating the effect of flow separation on the thermal performance of nanofluids using different configurations and boundary conditions, where researchers have studied the effect of the characteristic change in geometry flow on heat transfer in the nanofluid flow under contraction and/or expansion, as well as the influence of flow recirculation on the thermal performance of the nanofluids used (ABU TALIB and SALMAN, 2023; AVECILLA et al., 2024; GÜRSOY et al., 2022; KIMOUCHE et al., 2017; KLAZLY and BOGNAR, 2022; MONTAZER et al., 2020b; SAFAEI et al., 2021a; TOGUN et al., 2023a, 2023b; TOGUN et al., 2017; YANG et al., 2021). The thermophysical properties of nanoparticles, the type of base fluid used, the heat transfer mechanisms for different processes, as well as the nature of the flow under changing geometry are reviewed. The main challenges and difficulties in this field, specifically in experimental work, are discussed. Finally, the potential gains in heat transfer reported by the authors are listed throughout this chapter.

The use of annular pipes with sudden geometry change for fluid flow are used in various engineering applications such as heat exchangers, gas turbines, nuclear reactor cooling and some industrial operations such as cementing, fracturing, lubricant flow in rolling bearings and pressure bushes (KAZI and TOGUN, 2015). (BAUGHN *et al.*, 1984) investigated the local heat transfer coefficient for air flow downstream of an abrupt axisymmetric expansion in a circular duct with constant heat flux in the wall. The results obtained showed that for a given expansion radius, the peak for the fully developed Nusselt number decreased as the Reynolds number increased, however the rate of decay became small at the upper end of the range covered by the Reynolds number in these experiments. (TOGUN *et al.*, 2016a) experimentally investigated the heat transfer for air flow in the turbulent regime through an annular pipe with axisymmetric sudden expansion. Through the experimental results, the authors reported that the Nusselt number for the inlet and outlet of the pipe increases with increasing expansion radius for the outer and inner part of the test section, where the maximum increase observed was 63 % – 78 % for the outer and inner part of the pipe. It was also observed that the temperature on the outer surface of the pipe decreases in the inlet region due to the recirculation zone generated by the sudden expansion.

(ROY *et al.*, 2010) numerically investigated the flow of air in the turbulent regime through a channel with sudden expansion, taking into account the effects of curvature on the flow line. The authors analyzed the variations in size and length of the recirculation zone formed by the effect of different Reynolds numbers and expansion radii. The authors reported that the turbulent kinetic energy obtained increased due to the increase in the recirculation zone obtained with an increase in the expansion radius. (OON *et al.*, 2012; TOGUN *et al.*, 2011) investigated the effect of air flow separation in an annular pipe with sudden expansion experimentally and numerically respectively. The authors focused on the influence of flow separation on the average and local heat transfer coefficient. Using both approaches, the authors concluded that the local heat transfer coefficient (h_x) increases with the Reynolds number in all the cases analyzed and that in the recirculation zone formed by the expansion, h_x increases with until it reaches a maximum value at the reattachment point. (TOGUN *et al.*, 2014a) numerically investigated heat transfer for air flow in an annular pipe with sudden contraction. The boundary conditions adopted were constant heat flux inside the pipe, turbulent flow and a contraction radius (CR) ranging from 1.2 to 2. The simulation results reported by the authors showed that the local heat transfer coefficient increased with increasing Reynolds number and CR. (ABDULRAZZAQ *et al.*, 2020b) conducted a comprehensive study, both numerically and

experimentally, on the heat transfer and turbulent flow behavior of nanofluids within an annular cylinder featuring a sudden contraction. Their findings revealed that an increase in the Reynolds number corresponds to a reduction in surface temperature. However, this temperature reduction is less significant near the outlet pipe, attributed to the abrupt decrease in the flow passage size (see Fig. 2.1).

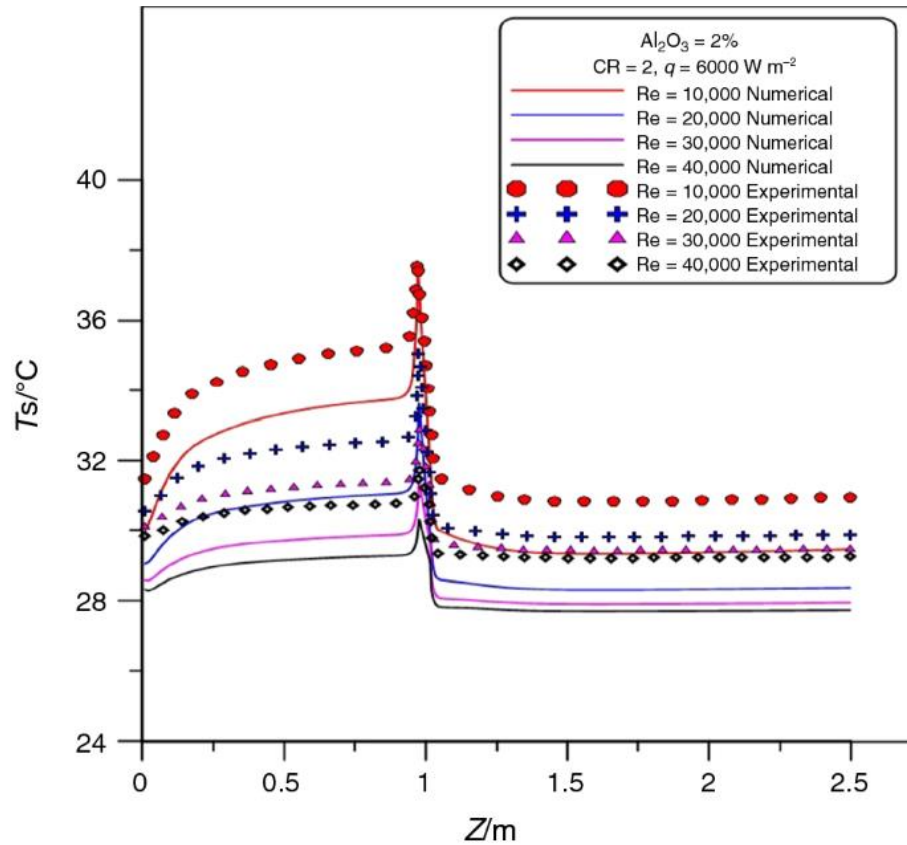


Figure 2.1 – Variations surface temperature with different Reynolds numbers. Source: (ABDULRAZZAQ et al., 2020a).

(BASHIR et al., 2019) experimentally investigated the heat transfer characteristics and pressure drop for water flow in the transition regime flowing in pipes with a square edge at the inlet and reentrance with different CRs. The experiments were conducted by the authors in a circular test section ranging from laminar to turbulent regime and constant heat flux at the pipe wall. The authors reported that the transition regime was significantly affected by lower CR and this effect was enhanced with increasing heat flux. It was also observed that, with increasing CR, the transition of the flow at the inlet with square edge occurs faster, while for the reentrant, the transition suffers a delay with increasing contraction radius. This phenomenon is schematized in Fig. (2.2a), which represents the influence of CR on the fully thermally

developed region for the square edge inlet (blue lines) and reentrant (green lines), and in Fig. (2.2b), where the qualitative description of the flow for different inlet types and flow patterns. According to the authors, different inlet conditions do not affect the heat transfer coefficients in the laminar and turbulent regimes, however, in the transition the flow is significantly affected.

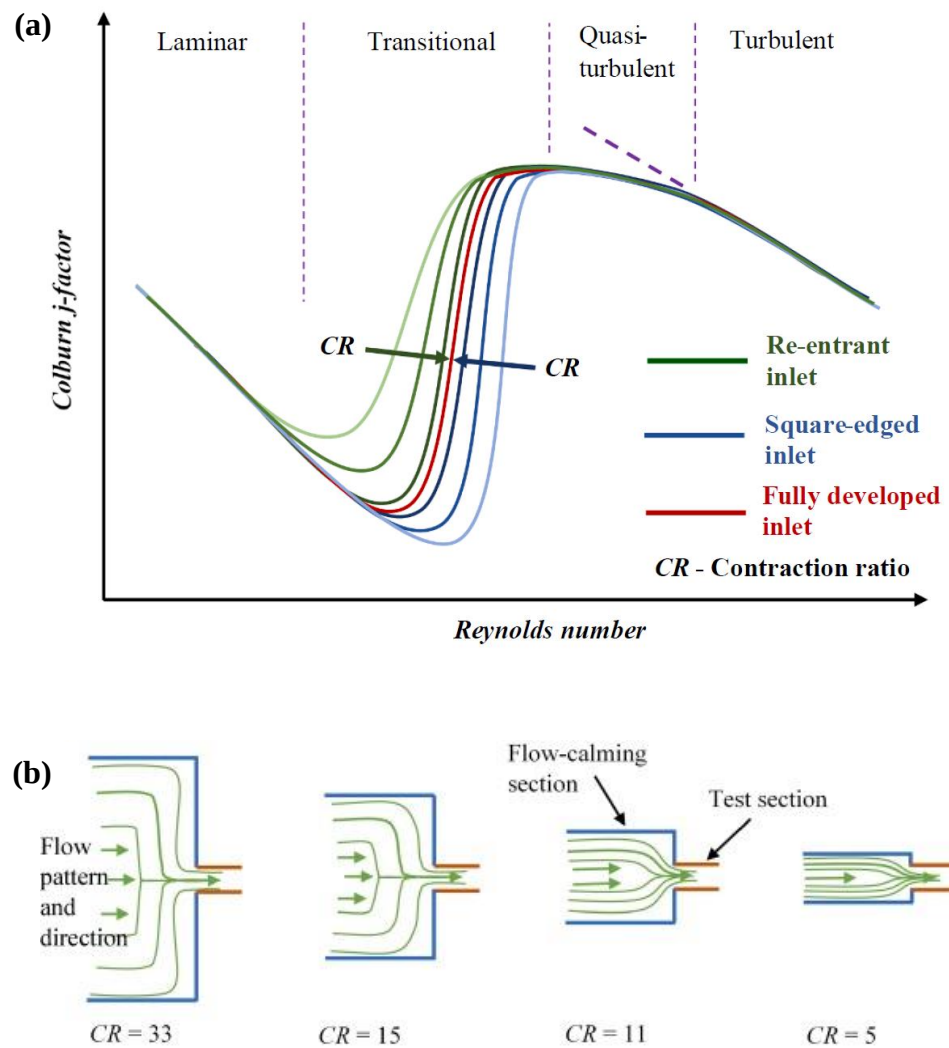


Figure 2.2 – (a) Schematic representation of the influence of CR on the fully developed Colburn j -factor as a function of Reynolds number for a square edge inlet (blue) and for reentrance (green). (b) Schematic diagram of the flow pattern for square edge inlets with different CR . Source: (BASHIR et al., 2019).

As indicated by the light and dark blue lines, an increase in the shrinkage radius leads to an early transition. The red line not only represents the results for the square edge geometries

at the inlet and re-entry when a large shrinkage radius is used, but also the hydrodynamically developed region at the inlet. The Colburn j-factor is used to directly relate the heat transfer coefficients, allowing the prediction of an unknown transfer coefficient when one of the other coefficients is known.

(TOGUN *et al.*, 2014b) numerically investigated the heat transfer in the laminar regime in flow over a BFS channel with and without obstacles. For the simulation, the heat flow was kept constant at the wall, for an expansion radius (ER) equal to 2 and different heights for the obstacles used. The results reported by the authors indicate that the effect of the obstacle height on the recirculation region leads to an increase in thermal performance. (XIE and XI, 2017) investigated through numerical simulation the flow characteristics and heat transfer of air in a BFS channel, considering the effects of Reynolds number and ER on the separation and reattachment of the flow. The authors reported that the size of the primary recirculation zone increased as the ER decreased and the Nusselt number increased as the Reynolds number increased for all the cases analyzed.

(TOGUN *et al.*, 2013a) numerically investigated heat transfer for air flow in a rectangular channel with a double backward facing step (DBFS). For the simulation, the authors considered the top of the wall and the bottom upstream as thermally insulated, and the bottom of the wall downstream of the flow being heated. The authors reported an increase in heat exchange particularly after passing through the first and second step due to the recirculation zone created. An increase in the Nusselt number was reported with increasing Reynolds number and decreasing step height. (ABDULRAZZAQ *et al.*, 2020a) numerically investigated the heat transfer in a channel with DBFS for different conventional fluids. The authors simulated the flow for three fluids: water, liquid ammonia and ethylene glycol, with Reynolds numbers ranging from 98.5 to 512, different step heights and constant thermal flow. It was reported that the local Nusselt number increased with increasing Reynolds number, and the critical effects were seen in the inlet area of the first and second steps, and the maximum average Nusselt number was obtained with ethylene glycol compared to the other fluids.

Many experimental and numerical studies aimed at enhancing heat transfer in the flow of nanofluids through axisymmetric pipes with sudden contraction and expansion, BFS channels, channels with FFS, and flow with obstacles have been carried out by researchers in recent years (see Fig.2.3). The separation region of the flow in annular channels occurs due to the change in pressure gradient caused by the sudden change in geometry of the flow. (ABDRABBUH *et al.*, 2022; SONG *et al.*, 2023; TOGUN *et al.*, 2017). This region is followed by turbulent

structures that affect heat transfer in thermal systems, as explained in the reviews of (ABDRABBUH et al., 2022; NATESAN and KARINKA, 2023; ROSERO et al., 2022; SAJID and ALI, 2019; TOGUN et al., 2014c).

This review covers research related to heat transfer in the flow of nanofluids under expansion and/or contraction in circular ducts, FFS, BFS and obstacle channels. The main objective of this chapter is to clarify the gains in energy terms for thermal systems through the flow of nanofluids in closed ducts with a change in geometry, as well as to illustrate the main challenges, such as the formation of recirculation zones and the use of these configurations for practical applications.

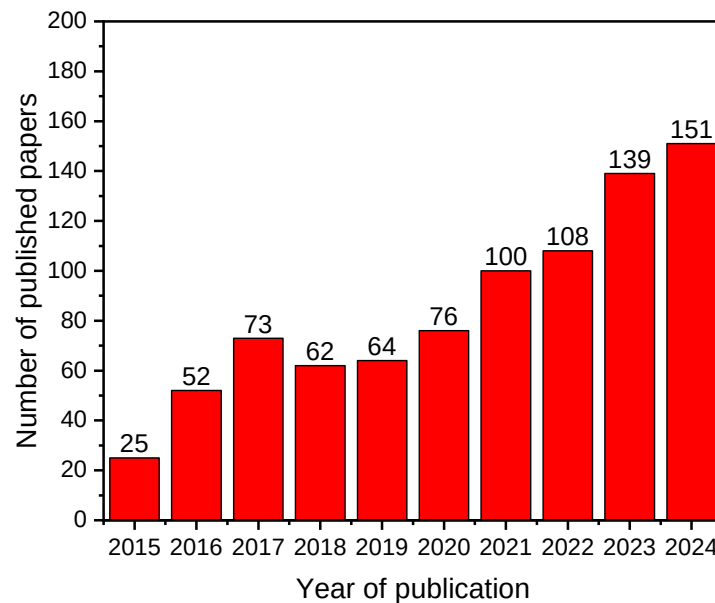


Figure 2.3 – Number of papers published with heat transfer, nanofluids, expansion and contraction as keywords published. Source: (www.sciencedirect.com).

2.2 Nanofluids

Nanofluids, an emerging class of engineering materials, consist of base fluids infused with nanometer-scale additives typically measuring less than 100 nanometers (BACHA *et al.*, 2024). (MAXWELL, 1873) pioneered the reporting of enhanced thermal conductivity in conventional fluids, despite challenges such as erosion, clogging, and sedimentation in flow paths. This enhancement is crucial for improving thermal characteristics and facilitating heat conversion processes (LI *et al.*, 2009a). However, the observed behavior of nanofluids often

deviates significantly from conventional macroscopic theories, highlighting the urgent need for a new theoretical framework that accurately accounts for the unique properties of nanofluids. Although efforts (HAMILTON and CROSSER, 1962) have explored potential heat transfer mechanisms, the primary challenge remains in attaining a detailed understanding at the atomic and microscale levels of how heat propagates within nanofluids. Understanding these mechanisms is crucial to fully realize the potential of this emerging class of heat transfer fluids, especially in cases where stability depends on the predominance of Brownian motion over gravitational settling, contingent upon the size of the particles (EASTMAN *et al.*, 2004; HAUSER, 1955).

Nanofluids are widely used: to enhance heat transfer in industrial cooling and heating systems, as smart fluids, in nuclear reactors, for geothermal and other energy extraction, and in space and defense applications. They are also employed in mass transfer processes and automotive applications, serving as coolants, brake fluids, and fuel additives. In electronics, nanofluids are used for cooling microchips and in microscale fluidic systems. Biomedical applications of nanofluids include nano drug delivery, cancer therapy, nano-cryosurgery, sensing, and imaging. Furthermore, nanofluids are incorporated into detergents, utilized in mechanical applications for friction reduction and magnetic sealing, and applied in energy sectors for energy storage and solar absorption (ALHARBI *et al.*, 2024; FARINHA, 2023; VIDYA *et al.*, 2023); in mechanical applications such as for friction reduction, magnetic sealing; in energy application such as energy storage, solar absorption (CHAMSA-ARD *et al.*, 2017; DAS *et al.*, 2023; MOHAMMAD *et al.*, 2021; TEKIR *et al.*, 2022), etc.

Nanoparticles are employed extensively across various studies and come in a range of types, including metals such as gold (Au), nickel (Ni), silver (Ag), and copper (Cu) (CHEN *et al.*, 2017; PAVITHRA *et al.*, 2021; SALEH and SUNDAR, 2021; SHAHZAD *et al.*, 2022). They also include metal oxides like aluminum oxide (Al_2O_3), zirconium oxide (ZrO_2), magnetic oxides, zinc oxide (ZnO), silicon dioxide (SiO_2), ferric oxide (Fe_2O_3), titanium dioxide (TiO_2), and copper oxide (CuO) (SAIDINA *et al.*, 2020; SUGANTHI and RAJAN, 2017; SUJITH *et al.*, 2022; TUOK *et al.*, 2023; YASMIN *et al.*, 2023; ZABOUR *et al.*, 2022). Carbon-based materials, such as diamond, carbon nanotubes, and graphene, are also significant contributors. Additionally, metal nitrides like aluminum nitride (AlN) and boron nitride (BN), as well as metal carbides such as silicon carbide (SiC), further diversify the spectrum of nanoparticles utilized in nanofluid research (BACHA *et al.*, 2024). Fig. (2.4) presents a flow chart that extensively illustrates the various classes of nanofluids.

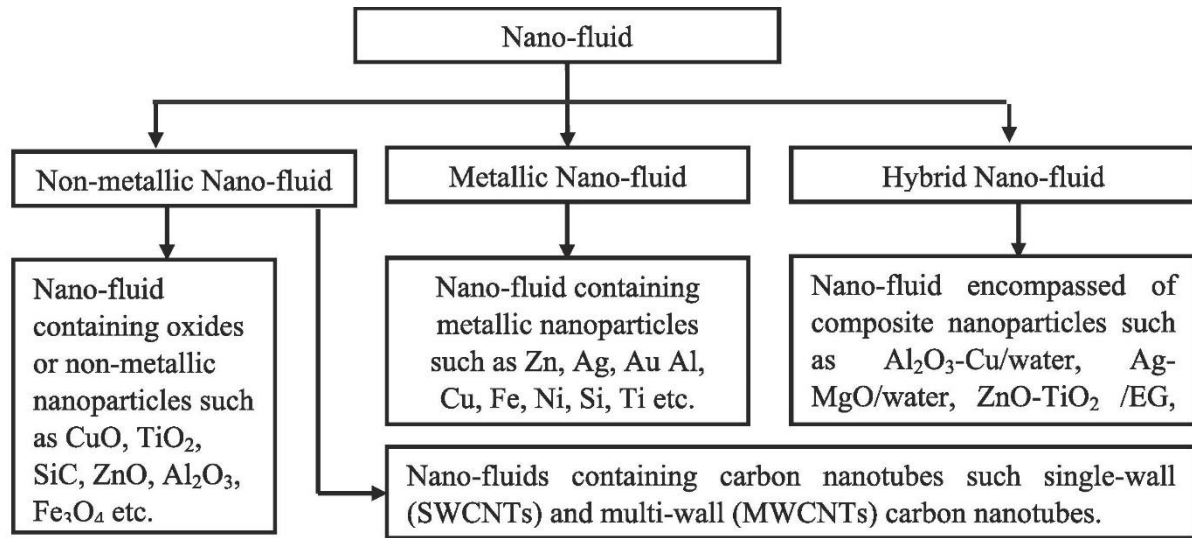


Figure 2.4 – Segregation of Nano-fluids depending on the dispersion of various nanoparticles in base fluids. Source: (AWAIS *et al.*, 2020).

The capability to manipulate or design the diverse thermophysical properties of these fluids, both individually and in combination, offers a promising avenue for significantly improving overall system performance (YOUNES *et al.*, 2022a). Notably, incorporating nanoparticles with high thermal conductivity into the fluids presents a key opportunity to enhance the thermal conductivity of the coolant fluids (SIMPSON *et al.*, 2018). These nanoparticles may include metals, metal oxides, carbon nanotubes, or graphene, while the base fluids commonly used are water, ethylene glycol (EG), polyalphaolefin (PAO), among others (COCCIA *et al.*, 2021; LENIN *et al.*, 2021; SIMPSON *et al.*, 2018; TAWFIK, 2017; WOHLID *et al.*, 2022; YOUNES *et al.*, 2022a). Table 2.1 shows the thermal conductivity values for some solid materials used in the production of nanoparticles and for the base fluids.

According the several finds presented in the literature heat transfer enhancement of nanofluids is influence principally by:

- Nanoparticle Clustering: Aggregation of nanoparticles in the fluid can affect heat transfer.
- Brownian Motion: The random thermal movement of nanoparticles impacts their dispersion and thermal conductivity.
- Ballistic Transport and Nonlocal Effects: These factors influence heat transfer at the nanoscale.

- Thermophoretic Effect: Temperature gradients can cause nanoparticle movement, altering heat transfer properties.
- Nanolayering at the Liquid/Nanoparticle Interface: Molecular-level layers formed at the interface affect heat transmission significantly.
- Near-Field Radiation: Radiation effects at short distances contribute to heat transfer enhancement.

Table 2.1 – Thermal conductivity of some materials, base fluids and nanofluids.

Classes	Materials	Thermal Conductivity (W/mK)
Metallic materials	Copper	421
	Silver	429
Nonmetallic materials	Silicon	148
	Alumina (Al ₂ O ₃)	40
Carbon	Carbon Nanotubes	2000 – 6000
	Graphene	4000
Base Fluids	Water	0.613
	Ethylene Glycol (EG)	0.253
	Engine Oil	0.145

Source: Adapted from (PRASAD et al., 2017).

2.2.1 Preparation of nanofluids

Nanofluids are produced by dispersing solid particles on a nanometer scale in base fluids with low thermal conductivity such as water, ethylene glycol, oil, etc. (LI *et al.*, 2020). The control of thermal performance in energy systems is crucial due to the increase in energy costs worldwide. Thus, in the last three decades, nanofluids have been receiving considerable attention in the field of nanotechnology, thermal engineering, and other important applications (CHAKRABORTY and PANIGRAHI, 2020). Quantitative evidence of the increase in thermal conductivity and performance of different nanofluids has been reported by several researchers (ALKASMOUL et al., 2022; JIN et al., 2022; KANTI et al., 2022; LIN et al., 2023; PAWAR et al., 2024; SELVARAJOO et al., 2024; VAKA and WALVEKAR, 2023; YU et al., 2024).

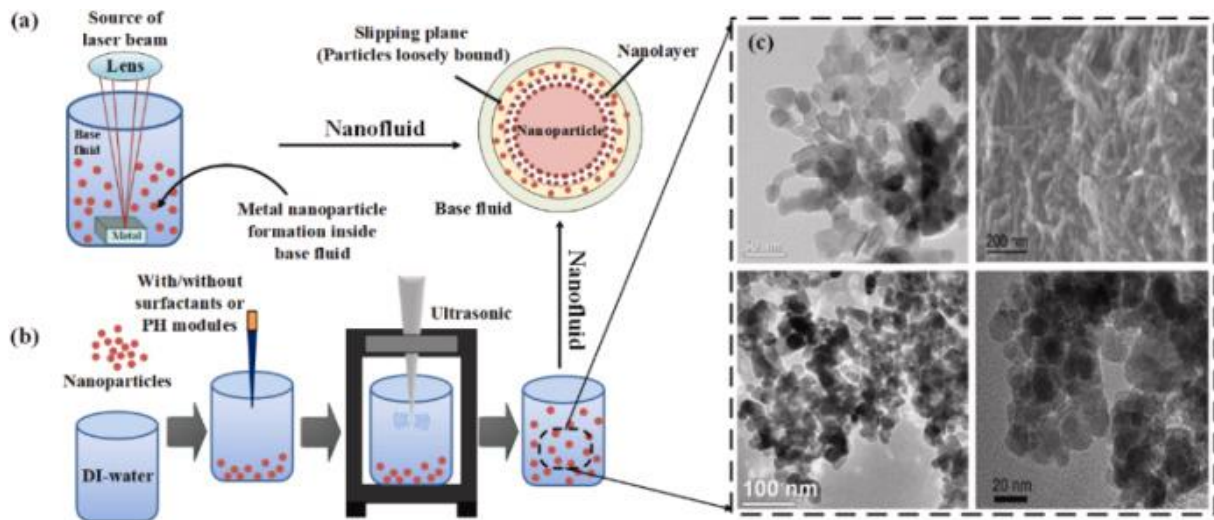


Figure 2.5 – Preparation process of nanofluids: (a) one-step method, (b) two-step method, and (c) SEM images of Al_2O_3 nanoparticles and CNTs nanoparticles, TEM images of ZnO nanoparticles and Fe_3O_4 nanoparticles. Source: (WANG *et al.*, 2023).

The preparation of nanofluids is the initial step for experimental analysis. With different volume or mass fractions of nanoparticles, nanofluids are produced by applying similar amounts of nanoparticles to the base fluid (HAQUE *et al.*, 2021). The suitable preparation of nanofluids plays a fundamental role in improving thermal properties by preventing nanoparticles decanting into the base fluid and instabilities (YANG *et al.*, 2020). Two techniques are currently used to disperse nanoparticles in the base fluid: the one-step method and the two-step method, Fig. (2.5). The one-step method consists of simultaneously producing and dispersing the particles in a fluid by physical vapor decomposition (PVD). This technique avoids the drying, storage, transportation and dispersion of nanoparticles, which reduces agglomeration and increases the stability of the suspensions in the base fluid (CHAKRABORTY and PANIGRAHI, 2020). However, using this method, the nanofluid is produced in batches, which makes it difficult to control important parameters such as concentration, product quantity and nanoparticle size, limiting its commercial viability (LI *et al.*, 2009b). The two-step method is the most widely used in the synthesis of nanofluids, considering that different types of nanoparticles are commercially available (SEZER *et al.*, 2019). In this technique, the nanoparticles are first synthesized as a dry powder using the inert gas condensation (IGC) process, and then dispersed in the base fluid (YANG *et al.*, 2020). The advantage of this method over the one-step method is its high production capacity and low cost. For nanofluids with metallic nanoparticles, the two-step method is not the most appropriate due

to the high oxidation potential (YANG *et al.*, 2020). The two-step method has potential economic benefits because in this way, many companies are able to produce nanoparticles on a large scale (SURESH *et al.*, 2011).

The main disadvantage of this method is controlling the clumping tendencies of nanoparticles due to Van Der Waals molecular forces, which leads to the extensive use of ultrasonication, surfactants and magnetic stirring to mitigate this effect (AFSHARI *et al.*, 2022; CHAKRABORTY and PANIGRAHI, 2020). Various types of surfactants have been used in the literature (Fig. 2.6), the most prominent being anionic surfactants, which have a negatively charged polar head, (Sodium Dodecyl Sulphate (SDS), Sodium Dodecyl Benzene Sulphonate (SDBS)), cationic, which has a positively charged polar head, (Cetylmethylammonium Bromide (CTBA)), non-ionic, which do not have charges that cause influence from the environment, (Polyvinil Pyrrolidone (PVP), Gum Arabic (GA)), amphoteric, which are surfactant compounds with acidic and alkaline properties, (alkylamidopropylamine N-oxide (APAO), alkyltrimethylamine N-oxide (AO), alkylbetaine (Bt), alkylamidopropylbetaine (APB)) etc., to significantly improve the stability of nanofluids produced by the two-step method (ABDELRAZEK *et al.*, 2020; AFSHARI *et al.*, 2022; BAI *et al.*, 2020; CACUA *et al.*, 2020; CHOWDHURY *et al.*, 2022; WANG *et al.*, 2023).

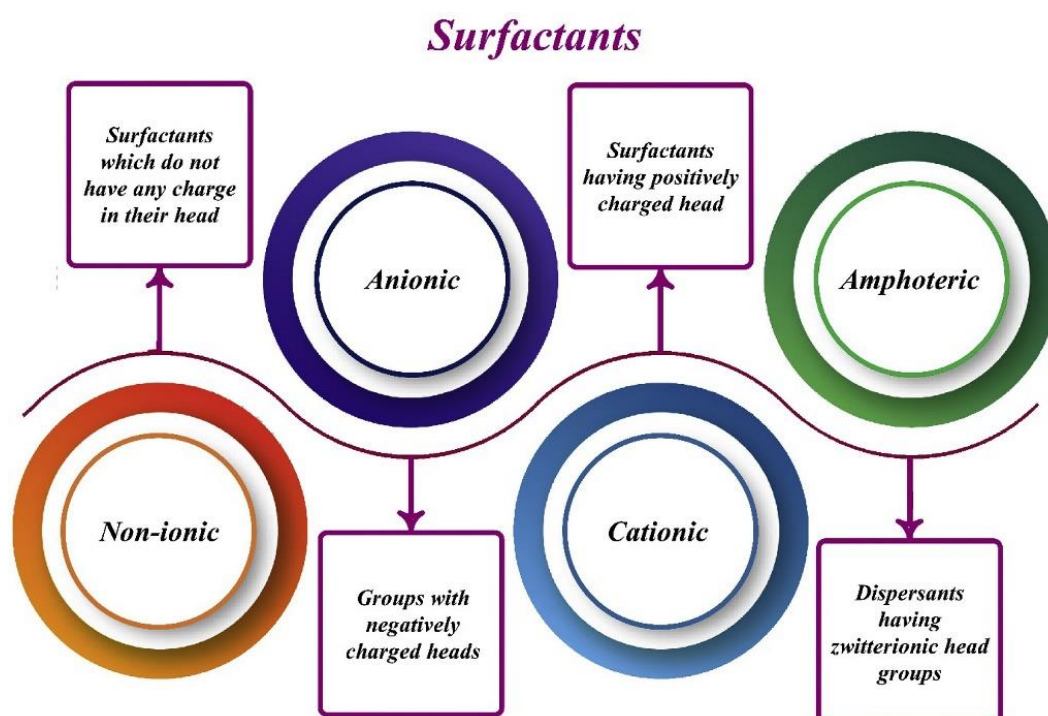


Figure 2.6 – Classification of surfactants based on head composition. Source: (YANG *et al.*, 2020b)

2.2.2 Nanofluid Effective Properties

Accurate prediction of nanofluid heat transfer behavior necessitates a thorough understanding of their thermophysical properties. The integration of nanoparticles, which possess unique thermophysical characteristics, alters the properties of conventional working fluids (KALSI *et al.*, 2023). Notable thermophysical properties of nanofluids include thermal conductivity, viscosity, specific heat capacity, and density. The inclusion of nanoparticles in the base fluid can lead to significant enhancements in thermal conductivity, viscosity, density, and specific heat, thereby influencing convective heat transfer (ARSLAN *et al.*, 2021; PRASAD *et al.*, 2017; SAID and SAIDUR, 2017). The thermophysical parameters of nanofluids are affected by various factors, including the size, shape, concentration, and type of nanoparticles, as well as the inherent properties of the base fluid (ALI and SALAM, 2020; GUPTA *et al.*, 2017; KALSI *et al.*, 2023).

Thermal conductivity

Several works on the literature show that thermal conductivity depends on a variety of factors such as: base fluid, addition of surfactant, nanoparticle concentration, temperature, nanoparticle size and shape (SIMPSON *et al.*, 2018). In certain instances, experimental findings are contradictory. Notably, the size and shape of nanoparticles play a crucial role in determining the thermal conductivity of nanofluids, whereas the material of the nanoparticles appears to have a less significant impact. Additionally, temperature and the volume concentration of nanoparticles markedly affect the thermal conductivity of nanofluids (GONÇALVES *et al.*, 2021; YOUNES *et al.*, 2022).

Thermal conductivity (κ) is a material's intrinsic property that quantifies its capability to conduct heat. It is mathematically represented as:

$$\kappa = \frac{Q/A}{dT/dx} \quad (2.1)$$

where Q is the amount of heat transmitted through a material with a cross-sectional area (A) due to a temperature gradient (dT/dx) across a distance (dx). It is measured in watts per meter-kelvin ($W/(mK)$), indicating the amount of heat in watts that can pass through a material one meter thick with a temperature difference of one Kelvin between its opposite faces.

Suspensions of nanoparticles in conventional heat transfer fluids exhibit anomalously enhanced thermal conductivity which cannot be explained and predicted by the typical classical models (YOUNES et al., 2022). Until recently, the mechanisms behind this enhanced thermal conductivity are neither fully understood nor conclusive in nature. The mechanisms responsible for the thermal transport enhancement of nanofluids has been the subject of much controversy in the scientific community over the last two decades. However, several mechanisms that were proposed in some of the earlier studies (MURSHED et al., 2009; WONG and CASTILLO, 2010) are now widely accepted by researchers as contributing to the thermal conductivity enhancement in nanofluids. These mechanisms include the formation of a nanolayer on the nanoparticle surface, Brownian motion of the nanoparticles, the nature of heat transport and the clustering or agglomeration of nanoparticles (MERCAN, 2022).

Several classical models are frequently employed to determine the thermal conductivity of nanofluids. These models based on the classical effective medium theory (EMT) for the thermal conductivity of fluids containing suspended solid particles are static models that assume motionless particles and diffusive heat transfer in both continuous matrix phase and dispersed phase. Although these static models can give a good thermal conductivity prediction for suspensions of micro- or millimeter-sized solid particles (WANG and MUJUMDAR, 2007), it was shown that they generally provide inaccurate thermal conductivity values for nanofluids. The first EMT-based model was proposed by Maxwell for a dilute solid–liquid mixture of non-interacting spherical particles. Although it was not specifically developed for nanofluids, this model, also known as Maxwell model (MAXWELL, 1873) and Maxwell–Garnett model (GARNETT, 1904), is one of the most used equations to predict the effective thermal conductivity of nanofluids. It is expressed as:

$$\frac{\kappa}{\kappa_f} = \frac{\kappa_p + 2 \cdot \kappa_f + 2 \cdot \varphi \cdot (\kappa_p - \kappa_f)}{\kappa_p + 2 \cdot \kappa_f + \varphi \cdot (\kappa_p - \kappa_f)} \quad (2.2)$$

where κ is the thermal conductivity of the nanofluid, κ_f is the thermal conductivity of the base fluid, κ_p is the thermal conductivity of the nanoparticles and φ is the volume fraction of nanoparticles. Being $\kappa_p \geq \kappa_f$ and $\varphi \leq 1$, so, the relationship with particle concentration is expected to be linear:

$$\frac{\kappa}{\kappa_f} \approx 1 + 3 \cdot \varphi \quad (2.3)$$

Based on the symmetrical EMT, (BRUGGEMAN, 1935) introduced a theoretical equation to examine the interactions among randomly dispersed particles. This model, applicable to a binary solid-liquid mixture with homogeneous spherical inclusions, is expressed as follows:

$$\varphi \cdot \left(\frac{\kappa_p - \kappa_{eff}}{\kappa_p + 2 \cdot \kappa_{eff}} \right) + (1 - \varphi) \cdot \left(\frac{\kappa_f - \kappa_{eff}}{\kappa_f + 2 \cdot \kappa_{eff}} \right) = 0 \quad (2.4)$$

The Bruggeman model performs effectively with spherical particles and is not constrained by particle concentration levels. It yields results comparable to those of the Maxwell model at low particle concentrations. However, at elevated particle concentrations, the Maxwell model does not align well with experimental observations, highlighting its limitations in such conditions (COCCIA et al., 2021).

(HAMILTON and CROSSER, 1962) generalized the Maxwell equation by introducing an empirical shape factor, n , to account for the influence of particle shape on the thermal conductivity of particle suspensions. When $\kappa_p/\kappa_b > 100$, the equation takes the following form:

$$\kappa_{eff} = \frac{\kappa_p + (n-1) \cdot \kappa_b - (n-1) \cdot (\kappa_b - \kappa_p) \cdot \varphi}{\kappa_p + (n-1) \cdot \kappa_b + (\kappa_b - \kappa_p) \cdot \varphi} \cdot \kappa_p \quad (2.5)$$

where the empirical factor n is defined as $n = \frac{3}{\psi}$, being ψ a parameter that considers the sphericity of the particles. For spherical particles mixture ($\psi = 1$), this equation simplifies to the original Maxwell equation.

(YU and CHOI, 2003a) modified the Maxwell equation to include the nanolayer's impact on thermal conductivity. The authors replaced the solid particle thermal conductivity (κ_p) with the modified thermal conductivity of equivalent particles (κ_{pe}), based on the effective medium theory (SCHWARTZ et al., 1995):

$$\kappa_{pe} = \frac{[2 \cdot (1-\gamma) + (1+\beta)^3 \cdot (1+2 \cdot \gamma) \cdot \gamma]}{-(1-\gamma) + (1+\beta)^3 \cdot (1+2 \cdot \gamma)} \cdot \kappa_p \quad (2.6)$$

where $\gamma = \kappa_{layer}/\kappa_p$ is the ratio of thermal conductivities between the nanolayer and the particle, and $\beta = 1 + h/r$ is the ratio of the particle with nanolayer thickness (h) to the original particle size. The Yu and Choi equation for the effective thermal conductivity of nanofluids is:

$$\kappa_{eff} = \frac{\kappa_{pe} + 2 \cdot \kappa_b + 2 \cdot (\kappa_{pe} - \kappa_b) \cdot (1 - \beta)^3 \cdot \varphi}{\kappa_{pe} + 2 \cdot \kappa_b + (\kappa_{pe} - \kappa_b) \cdot (1 - \beta)^3 \cdot \varphi} \cdot \kappa_p \quad (2.7)$$

Assuming a small volume fraction of particles and heat conduction through a random, stationary, and statistically homogeneous suspension of spherical particles in a matrix of uniform conductivity, (JEFFREY, 1973) proposed the following theoretical model:

$$\kappa_{eff} = \left[1 + 3 \cdot \beta \cdot \varphi + \varphi^2 \cdot \left(3 \cdot \beta^2 + \frac{3 \cdot \beta^3}{4} + \frac{9 \cdot \beta^3}{16} \cdot \frac{\chi + 2}{2 \cdot \chi + 3} + \frac{3 \cdot \beta^4}{2^6} + \dots \right) \right] \cdot \kappa_p \quad (2.8)$$

where

$$\beta = \frac{\kappa_p - \kappa_b}{\kappa_p - 2 \cdot \kappa_b} = \frac{\chi - 1}{\chi + 2} \quad (2.9)$$

and

$$\chi = \frac{\kappa_p}{\kappa_b} \quad (2.10)$$

(TIMOFEEVA *et al.*, 2007) later developed a simpler EMT-based correlation for the thermal conductivity of nanofluids:

$$k_{eff} = (1 + 3 \cdot \varphi) \cdot \kappa_b \quad (2.11)$$

This equation was modified to account for particle shapes (e.g., elongated and dendritic structures) and surface resistance (Kapitza resistance). The modified model, which incorporates additional parameters derived from experimental data regression, highlights the influence of nanoparticle geometry, agglomeration state, and surface resistance on the enhancement of k_{eff} .

(MURSHED et al., 2009) developed an advanced model that incorporates both static and dynamic mechanisms of nanoparticles, including nanolayer effects, particle size, concentration, interactions, and Brownian motion. The model is expressed as follows:

$$\begin{aligned}
 k_{eff-nf} = & k_f \frac{\varphi_p \omega (k_p - \omega k_f) [2\gamma_1^3 - \gamma^3 + 1] + (k_p + 2\omega k_f)\gamma_1^3 [\varphi_p \gamma^3 (\omega - 1) + 1]}{\gamma_1^3 (k_p + 2\omega k_f) - (k_p - \omega k_f)\varphi_p [\gamma_1^3 + \gamma^3 - 1]} \\
 & + \varphi_p^2 \gamma^6 k_f \left(3\Lambda^2 + \frac{3\Lambda^2}{4} + \frac{9\Lambda^3}{16} \frac{k_{cp} + 2k_f}{2k_{cp} + 3k_f} + \frac{3\Lambda^4}{2^6} + \dots \right) \\
 & + \frac{1}{2} \rho_{cp} c_{p-cp} d_s \left[\sqrt{\frac{3K_B T (1 - 1.5\gamma^3 \varphi_p)}{2\pi \rho_{cp} \gamma^3 r_p^3}} + \frac{G_T}{6\pi \eta \gamma r_p d_s} \right] \quad (2.12)
 \end{aligned}$$

The second term accounts for interactions between spherical particles in a stationary suspension, while the third term considers the effects of Brownian motion, particle surface chemistry, and inter-particle interactions. Similar to the Yu and Choi model (YU and CHOI, 2003a, 2004), the nanolayer thermal conductivity (κ_{lr}) cannot be determined experimentally or theoretically.

(SHUKLA *et al.*, 2016) developed an analytical model for the effective thermal conductivity of nanofluids, considering heat conduction and convective heat transfer from Brownian motion. The model predicts thermal conductivity based on nanoparticle volume fraction, diameter, shape, and temperature. It aligns well with the Hamilton–Crosser model and other empirical models for Al_2O_3 and TiO_2 in water and ethylene glycol, showing deviations under 8 % for spherical particles up to 0.25 % volume fraction. The model also indicates that non-spherical nanoparticles with larger volume-specific surface areas can achieve greater thermal conductivity enhancement. Eq. (2.13) shows the expression for the dimensionless effective thermal conductivity.

$$\frac{\kappa_{eff}}{\kappa_{bf}} = (1 - \varphi) + \pi \cdot \left(\frac{6}{\pi}\right)^{1/3} \cdot \varphi^{4/3} \cdot \left[\frac{1 + 0.5 \cdot \left(\frac{6}{\pi}\right)^{1/3}}{2} \cdot \left(\frac{\kappa_{bf}}{\kappa_p}\right) + \frac{\psi}{Nu} \right]^{-1} \quad (2.13)$$

Three different contributions can be seen in Eq. (2.13). The first term $(1 - \varphi)$ accounts for the bulk fluid's volume fraction, the second term relates to the nanoparticles, including conduction through the particles κ_p and convective heat transfer between the particles and bulk fluid (ψ/Nu) .

(HOSSEINI *et al.*, 2017) developed a dimensionless model to predict the effective thermal conductivity of nanofluids, incorporating nanoparticle and base liquid conductivity, nanoparticle size, volume fractions, and interfacial shell properties. The model results in a non-linear correlation for thermal conductivity, showing good compatibility with experimental data for Al₂O₃/H₂O nanofluids compared to other models. Eq. (2.14) shows the generical form of dimensionless for effective thermal conductivity.

$$\frac{\kappa_{nf}}{\kappa_m} = 1 + \lambda \cdot \left[\left(\frac{\kappa_i}{\kappa_p} \right)^\alpha \cdot \left(\frac{t}{d_p} \right)^\beta \cdot (\nu_p)^\gamma \cdot \left(\frac{T}{T_0} \right)^\zeta \right] \quad (2.14)$$

where α , β , γ and ζ are constants that depend to the nanofluid type. κ_i , κ_p , κ_m and κ_{nf} are the conductivity of interfacial shell, solid particle, base fluid and nanofluid. ν_p is the volume concentration and T is the temperature in Kelvin.

(ALAWI *et al.*, 2018) proposed a model for thermal conductivity of Al₂O₃, CuO, SiO₂ and ZnO nanoparticles based on water with volume concentration of 1 % – 5 % at 300 K – 320 K. According to the authors the thermal conductivity enhances with temperature and nanoparticle concentration but decreases with nanoparticle size intensifies. Eq. (2.15) shows the proposed model.

$$\frac{\kappa_{eff}}{\kappa_f} = 1 + (C_p^{Shape} + C_p^{Surface}) \cdot \varphi = 1 + C_p^\varphi \quad (2.15)$$

where C_p is the specific heat.

(ONYIRIUKA, 2023) introduced a "model of models" approach to predict the thermal conductivity of nanofluids. This method combines three data streams: experimental data, previous study correlations, and theoretical data, as inputs for a primary machine learning model. By integrating these streams, the model addresses challenges in predicting nanofluids' thermophysical properties, achieving a high accuracy with an R-squared value of 0.999. Additionally, the study compares various machine learning algorithms and models, evaluating their performance with metrics like RMSE, MSE, R-squared, and MAE.

(RASHIDI *et al.*, 2023) modeled the thermal conductivity of ethylene-glycol/water based nanofluids with alumina particles using Multi-Layer Perceptron (MLP) and Group Method of Data Handling (GMDH). Among MLP configurations, the radial basis function

provided the highest prediction accuracy, with R^2 values of 0.9998 for MLP with both tangent sigmoid and radial basis functions, and 0.9996 for GMDH. According to the authors sensitivity analysis identified base fluid thermal conductivity as the most influential factor in the nanofluid's thermal conductivity.

Specific heat

The specific heat capacity of nanofluids (C_p, nf) is determined by the average particle size (d_{np}), particle volume fraction φ_v , temperature (T), nanoparticle heat capacity (C_p, np), and base-fluid specific heat capacity (C_p, bf) (DEYMI *et al.*, 2023). Several correlations for the specific heat capacity of nanofluids have been developed, and some researchers have investigated this property using these equations. (Pak and Cho, 1998) proposed the following equation to measure the specific heat of nanofluids:

$$C_{nf} = (1 - \varphi_v) \cdot C_w + \varphi_v \cdot C_p \quad (2.16)$$

where (C) is the specific heat of the dispersed fluid, (nf) represents the nanofluid, (φ_v) is the volume fraction of nanoparticles, (p) represents particles, and (w) refers to water. Subsequent researchers have modified and updated this equation. (XUAN and ROETZEL, 2000) introduced a more accurate equation for experimental data:

$$(\rho \cdot C_p)_{nf} = (1 - \varphi) \cdot (\rho \cdot C_p)_f + \varphi \cdot (\rho \cdot C_p)_s \quad (2.17)$$

with the density of the nanofluid given by:

$$\rho_{nf} = (1 + \varphi) \cdot (\rho \cdot C_p)_f + \varphi \cdot (\rho \cdot C_p)_s \quad (2.18)$$

where C_p is the specific heat, ρ is the density, and φ is the volume fraction of nanoparticles. The subscripts nf , f , and s denote nanofluid, fluid, and solid, respectively.

(BUONGIORNO, 2006) proposed an improved model for calculating the specific heat of nanofluids. This model assumes thermal equilibrium between the particles and the fluid, expressed as:

$$(C_p)_{nf} = \frac{\varphi \cdot (\rho \cdot C_p)_{np} + (1 - \varphi) \cdot (\rho \cdot C_p)_{bf}}{(\varphi \rho)_{np} + (1 - \varphi) \cdot \rho_{bf}} \quad (2.19)$$

Although widely used in studies on thermal conductivity, diffusivity, and heat transfer of nanofluids (GAO *et al.*, 2021; HENTSCHKE, 2016; JAMEI *et al.*, 2021; RIAZI *et al.*, 2016; SEAWRAM *et al.*, 2022; SHAHRUL *et al.*, 2014), the validity this model, like others linear analytical models, remains questionable. Table 2.2 provides an overview of various regression-based models used to estimate the specific heat capacities of different nanofluids.

Table 2.2 – Regression models for specific heat of some metal-oxide based nanofluids.

Nanofluids	Model	Author
Al ₂ O ₃ /EG-water, ZnO/EG-water, SiO ₂ /deionized water	$\frac{(C_p)_{nf}}{(C_p)_{bf}} = \frac{\left[(A \times T) + \left(B \times \frac{(C_p)_{np}}{(C_p)_{bf}} \right) \right]}{C + \varphi}$ A, B, C are curving fit coefficient	(VAJJHA and DAS, 2009)
CuO/EG	$(C_p)_{nf} = \frac{\varphi \cdot (\rho \cdot C_p)_{np} + (1 - \varphi) \cdot (\rho \cdot C_p)_{bf}}{(C_p)_{np} \cdot (\varphi \rho)_{np} + (1 - \varphi) \cdot \rho_{bf}}$	(ZHOU <i>et al.</i> , 2010)
Nanoparticles: (Al ₂ O ₃ , CuO, SiO ₂ , ZnO, TiO ₂ and MgO) Base fluids: (Water, Deionized water, R134a, Ethylene glycol and mixtures)	$(C_p)_{nf} = \left[\frac{(C_p)_{np}}{(C_p)_{bf}} + (C_p)_{bf} \right] + \left[(C_p)_{bf}^{G2C3/\rho_p} / \rho_p^{(C_p)_{bf}} + G2C2 - G2C0 \right] + \sqrt{\rho_p}$ $+ (C_p)_{np} + \left[\varphi \cdot (\rho \cdot C_p)_{np} / G5C5 \times G5C3 \right] / (C_p)_{np}^{\rho_p - G5C9}$ G2C0, G2C2, G2C3, G5C5, G5C3, G5C9 are curving fitting	(JAMEI <i>et al.</i> , 2021)
Graphene Oxide- Al ₂ O ₃ /Water	$(C_p)_{nf} = a + b \cdot \varphi + c \cdot T + d \cdot \varphi^2 + e \cdot \varphi \cdot T + f \cdot T^2$ where a, b, c, d, e, and f are fitted by the experimental data, and T [°C] the temperature.	(GAO <i>et al.</i> , 2021)

Source: Author's own.

Density

Density is a critical property of nanofluids, as it directly affects the Nusselt number, friction factor and Reynolds Number. (PAK and CHO, 1998) proposed a two-phase mixture density relationship based on slurry flows, linking the mixture density with the densities of the nanoparticle and base fluid, as well as the concentration per unit volume (Eq. 2.20).

$$\rho_{nf} = \rho_{np} \cdot \varphi + \rho_{bf} \cdot (1 - \varphi) \quad (2.20)$$

where φ represents the volumetric concentration, while ρ_{nf} , ρ_{np} and ρ_{bf} denote the densities of the nanofluid, nanoparticle, and base fluid, respectively.

(VAJJHA and DAS, 2009) conducted density measurements of ZnO, Al₂O₃, and Sb₂O₅ nanofluids based on a mixture of water and ethylene glycol with a 60:40 mass ratio (60:40 % wt.), finding that Sb₂O₅ matched Pak and Cho's equation within 1.2 % deviation, while ZnO deviated by up to 8 %. (YOUSEFI and AMOOZANDEH, 2017) evaluated thermal properties of various nanofluids, including ZnO/polyethylene glycol – water and TiO₂/ethylene glycol, using Pak and Cho's equation and the extended state equation of Tao-Mason (YOUSEFI and KAVEH, 2012), also predicting isentropic compressibility and heat capacity with equation of state densities. (SAHALUDDIN *et al.*, 2020) used support vector regression to accurately predict the densities of silicon nitride, titanium nitride, and aluminum nitride in ethylene glycol, comparing their results with Pak and Cho's model. According to the authors their model accurately predicted the nanofluid densities and its results were compared with those from Pak and Cho's model to highlight its precision.

(SELVAKUMAR and WU, 2019) proposed a model for predicting the effective density of nanofluids, taking into account the density of clusters surrounded by the interfacial layer and primary nanoparticles. (SHARIFPUR *et al.*, 2016) experimentally investigated the densities of SiOx-Ethylene-Glycol/Water, SiO₂-Water, CuO-Glycerol, and MgO-Glycerol nanofluids across a temperature range of 10 °C to 40 °C and volume fractions of 1 % to 6 %. Their findings indicated that the densities of nanofluids generally exceed the values reported in the literature. (ZHELEZNY *et al.*, 2017) observed a decrease in the heat capacity and an increase in the density of isopropanol when Al₂O₃ nanoparticles were added.

(MONTAZER *et al.*, 2018) employed a response surface methodology (RSM) to examine the impact of design variables on the density of MWCNT – COOH and F – GNP nanofluids. According to the authors the proposed model evaluates densities based on

nanoparticle mass fraction, temperature, and the density ratios of the base fluid to the nanoparticles and base fluid densities. When compared with experimental data, the trained model showed a strong correlation between the experimental and predicted density values of MWCNT–COOH nanofluids, as indicated by high correlation coefficients (R) and low mean squared error (MSE). The quadratic equations that best fit the experimental data points for MWCNT–COOH and FGNP are given by Eq. (2.21) and Eq. (2.22), respectively:

$$\rho_{Pre(MWCNT-COOH)} = -0.00443 \cdot T^2 - 0.096 \cdot \varphi \cdot T - 0.02468 \cdot T + 18.4 \cdot \varphi + 1000.15 \quad (2.21)$$

$$\rho_{Pre(F-GNP)} = -0.00518 \cdot T^2 - 25.6 \cdot \varphi^2 - 0.0184 \cdot \varphi \cdot T + 0.01741 \cdot T + 2.456 \cdot \varphi + 999.886 \quad (2.22)$$

where φ is the nanoparticles weight fraction and T is the temperature.

(YADAV *et al.*, 2021) presented regression analysis on the density of Al_2O_3 , CuO and CeO_2 based on ethylene glycol (EG) as base fluid. The results presented by the authors show that the density of these nanofluids varies linearly with temperature and concentration. A regression analysis proposed established correlations for density based on these parameters, resulting in four accurate equations for different nanofluid categories (Eq. (2.23) – Eq. (2.26)). These equations do not require particle or base fluid density data for predictions.

$$\rho = 1.12809 + 0.02693 \cdot \varphi - 0.000688095 \cdot T, \text{ for } 13 \text{ nm } Al_2O_3/EG \quad (2.23)$$

$$\rho = 1.12715 + 0.02545 \cdot \varphi - 0.00067044 \cdot T, \text{ for } 50 \text{ nm } Al_2O_3/EG \quad (2.24)$$

$$\rho = 1.11274 + 0.09435 \cdot \varphi - 0.000508352 \cdot T, \text{ for } 50 \text{ nm } CuO/EG \quad (2.25)$$

$$\rho = 1.128 + 0.05944 \cdot \varphi - 0.000690293 \cdot T, \text{ for } 25 \text{ nm } CeO_2/EG \quad (2.26)$$

In heat transfer applications, the density of nanofluids is a critical parameter for determining Reynolds number, Nusselt number, friction factor, and pressure drop. The literature survey reveals that density parameters have been considerably less examined than thermal conductivity and viscosity parameters.

Dynamic viscosity

Viscosity is a critical property influencing fluid flow characteristics. It directly affects pumping power, pressure drop in laminar flow, and convective heat transfer. Therefore, analyzing viscosity is essential for understanding the thermo-fluidic behavior of heat transfer fluids (MISHRA *et al.*, 2014).

(EINSTEIN, 1906) was the pioneer on the development of a nanofluid viscosity correlation (Eq. (2.27)), based on the assumption of viscous fluid containing spherical particles at low volume concentration ($\varphi < 0.02$).

$$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5 \cdot \varphi \quad (2.27)$$

being φ volume concentration, μ_{nf} and μ_f respectively the nanofluid viscosity and base fluid viscosity. This model indicates a linear increase in viscosity with particle volume concentration. However, it assumes non-interacting suspensions and has limitations, as it does not account for particle structure, particle-particle interactions, or high particle concentrations.

(BRINKMAN, 1952) expanded upon Einstein's equation to accommodate moderate particle concentrations. He addressed the impact of adding solute molecules to a continuous medium with particle concentrations below 4 %. This correlation is more accepted among researchers. The empirical formula is expressed as:

$$\mu_{nf} = (1 - \varphi)^{2.5} \cdot \mu_f \quad (2.28)$$

(LUNDGREN, 1972) proposed a reduction of Einstein's formula through a Taylor series expansion of φ , as can be seen in Fig. (2.29).

$$\mu_{nf} = \left[1 + 2.5 \cdot \varphi + \frac{25}{4} \cdot \varphi^2 + f(\varphi^3) \right] \cdot \mu_f \quad (2.29)$$

(GRAHAM, 1981) proposed a generalized version of the Franken – Acrivos (FRANKEL and ACRIVOS, 1967) model (Eq. 2.30) by incorporating particle radius and inter-particle spacing, aligning it with Einstein's formula for small φ . The model is given by Eq. (2.31).

$$\frac{\mu_{nf}}{\mu_f} = \frac{9}{8} \cdot \left[\frac{\left(\frac{\varphi}{\varphi_m}\right)^{1/3}}{\frac{(\varphi_m - \varphi)^{1/3}}{\varphi_m^{1/3}}} \right] \quad (2.30)$$

$$\mu_{nf} = \mu_f \cdot \left(1 + 2.5 \cdot \varphi + 4.5 \cdot \left[\frac{1}{\left(\frac{h}{d_p} \cdot \left(2 + \frac{h}{d_p}\right)\right) \cdot \left(1 + \frac{h}{d_p}\right)^2} \right] \right) \quad (2.31)$$

where h represents the inter – particle spacing and d_p denotes the particle radius.

(PAK and CHO, 1998) presented a viscosity model that considers particle volume fraction, using room temperature as a reference point. They observed that the viscosity of nanofluids is influenced by temperature, noting that viscosity decreases as temperature rises. Their model is represented by:

$$\mu_{nf} = \mu_f \cdot (1 + 39.11 \cdot \varphi + 533.9 \cdot \varphi^2) \quad (2.32)$$

(KULKARNI et al., 2006) developed a temperature-dependent viscosity model for CuO–water nanofluids in the 5 °C – 50 °C range. This model shows an exponential decrease in viscosity with increasing temperature. The mathematical expression is:

$$\ln(\mu_{nf}) = -(2.8751 + 53.548 \cdot \varphi \cdot 107.12 \cdot \varphi^2) + \frac{(1078.3 + 15857 \cdot \varphi + 20587 \cdot \varphi^2)}{T} \quad (2.33)$$

where T is the temperature in Kelvin.

(AVSEC and OBLAK, 2007) presented a viscosity model based on Ward model (WANG et al, 1999), see Eq. (2.34), and Einstein model. The correlation is presented in Eq. (2.35).

$$\frac{\mu_{nf}}{\mu_f} = [1 + \eta \cdot (\varphi_{eff} + 2.5 \cdot \eta + (2.5 \cdot \eta)^2 + \dots)] \quad (2.34)$$

$$\frac{\mu_{nf}}{\mu_f} = [1 + 2.5 \cdot (\varphi_{eff} + 2.5 \cdot \varphi_{eff} + (2.5 \cdot \varphi_{eff})^2 + \dots)] \quad (2.35)$$

In the model, φ_{eff} is the effective volume concentration, which can be calculated using the following relation based on the Yu and Choi model (Yu and Choi, 2003b):

$$\varphi_{eff} = \varphi \cdot \left(1 + \frac{h}{r}\right)^3 \quad (2.36)$$

where h represents liquid thickness.

(ABU-NADA, 2009) presented a correlation for $\text{Al}_2\text{O}_3/\text{water}$ nanofluids (Eq. (2.37)). He found viscosity as a function of temperature and volume concentration.

$$\begin{aligned} \mu_{nf} = & -0.155 - \frac{19.582}{T} + 0.749 \cdot \varphi + \frac{2094.47}{T^2} - 0.192 \cdot \varphi^2 - 8.11 \cdot \frac{\varphi}{T} - \frac{27463.863}{T^3} + 0.127 \cdot \\ & \varphi^3 + 1.6044 \cdot \frac{\varphi^2}{T} + 2.1754 \cdot \frac{\varphi}{T^2} \end{aligned} \quad (2.37)$$

(MASOUMI et al, 2009) established a theoretical model based on Brownian motion of particles to determine nanofluid's viscosity, and it's valid for $\text{Al}_2\text{O}_3/\text{water}$ nanofluids, Eq. (2.38).

$$\mu_{nf} = \mu_f \cdot \left(1 + \frac{\rho_N \cdot V_b \cdot d_N^2}{72 \cdot C \cdot \delta \cdot \mu_f}\right) \quad (2.38)$$

where ρ_N is the density, d_N the particle diameter, δ denotes the distance between the nanoparticles and C and V_b are two parameters depending on the temperature.

(HOSSEINI et al, 2010) developed an empirical correlation specifically for $\text{Al}_2\text{O}_3/\text{water}$ nanofluids. This dimensionless model incorporates volume concentration, nanoparticle size, temperature, and the capping layer effect, with parameters determined using least squares regression. The formula is:

$$\frac{\mu_{nf}}{\mu_f} = \exp \left[m + \alpha \cdot \left(\frac{T}{T_0} \right) + \beta \cdot (\varphi_h) + \gamma \cdot \left(\frac{d}{1-r} \right) \right] \quad (2.39)$$

where φ_h is the hydrodynamic volume fraction of nanoparticles, d is the nanoparticle diameter, r is the capping layer thickness, T_0 is the reference temperature, T is the measured temperature of the nanofluid, and m , α , β , and γ are constants determined experimentally.

(SURESH *et al.*, 2011) proposed a mathematical expression for measuring viscosity that accounts for electromagnetic, mechanical, and geometrical effects. The expression is:

$$\frac{\mu_{nf}}{\mu_f} = 1 + b \cdot \left(\frac{\varphi}{1-\varphi_m} \right)^n, \text{ being } (b) \text{ and } (n) \text{ constants} \quad (2.40)$$

(UDAWATTHA *et al.*, 2019) developed a correlation for calculating the effective viscosity of nanofluids. This model considers the effect of an interfacial layer on the nanoparticle, where the interfacial layer acts as a solid-like layer between the base fluid and the nanoparticle surface. The effective viscosity is a combination of the static and dynamic components of nanofluid viscosity, which can be expressed as follows:

$$\mu_{nf} = \mu_f \cdot \left(1 + 2.5 \cdot \varphi_e + \frac{\rho_N \cdot V_b \cdot d_N^2}{72 \cdot \delta \cdot T \cdot 10^{-10} \cdot \varphi^{-0.002} \cdot T - 0.284} \right) \quad (2.41)$$

this equation is a modification of Masoumi model where φ_e is the effective volume concentration, φ the volume concentration. The other parameters are as described in Eq. (2.38).

(FADHL *et al.*, 2023) proposed two intelligent approaches - Adaptive Neuro - Fuzzy Inference System (ANFIS) and Group Method of Data Handling (GMDH) for modeling the dynamic viscosity of nanofluids with MgO nanoparticles. Comparison of the values predicted by these methods with actual data demonstrated the effectiveness of both approaches. However, GMDH showed superior accuracy based on statistical criteria, with R^2 values of 0.9996 for GMDH and 0.9616 for ANFIS. The Average Absolute Relative Deviation (AARD) was approximately 5.13 % for GMDH and 19.41 % for ANFIS, indicating that GMDH is preferred for its higher accuracy.

The viscosity models discussed are commonly used to measure the viscosity of nanofluids. However, more attention is needed on the criteria for validating these models against experimental results and addressing their limitations. There is a lack of data on the optimal size of nanoparticles for achieving better stability and minimizing agglomeration. Further research is necessary to develop new viscosity models for nanofluids with various materials. Recent studies indicate that increased viscosity leads to higher pumping power, highlighting the need for alternative methods to replace conventional coolants with nanofluids.

2.2.3 Nanofluid stability

Nanofluids cannot be considered as simple suspensions of solid particles in liquids. Due to their small size, nanoparticles have a high surface energy, which tends to cause agglomeration and, subsequently, decantation (YANG *et al.*, 2020). In this sense, the dispersion of nanofluids has been considered a long-standing challenge, which limits their practical applications (YU *et al.*, 2017). The factors that most affect the stability of nanofluids produced by the two-step method are: concentration, the use of surfactants, the viscosity of the fluid, pH, the nature of the nanoparticles, the diameter of the nanoparticles and the sonication time. Using the right method to improve the stability of the nanoparticles in the base fluid is essential for developing dispersion strategies and exploring the practical applications of nanofluids in thermal systems (YU *et al.*, 2017). Fig. (2.7) illustrates the different methods for evaluating the stability of nanoparticles, such as the Zeta potential, which is a critical indicator of dispersion and stability, especially for water-based nanofluids. The Zeta potential is the difference in electrical potential between the dispersant medium and the stationary layer of the fluid to which the dispersed nanoparticle is attached (CHAKRABORTY and PANIGRAHI, 2020; YANG *et al.*, 2020; YU *et al.*, 2017). Spectral absorbance analysis is generally used when the nanoparticle suspended in the base fluid has an absorbance peak between 190 nm and 1100 nm (CHAMSA-ARD *et al.*, 2017), with this method, stability is measured by constantly checking the characteristic absorbance peak using UV-VIS spectrophotometry and how it varies with time (CHAKRABORTY and PANIGRAHI, 2020). The centrifugal method, used in stability studies, in which a visual examination of the sedimentation of nanofluids is made using a centrifugal dispersion analyzer (ALI *et al.*, 2018). Among all these, sedimentation is a primary method of evaluating and visualizing the dispersion and stability of nanofluids, in which due to the difference in density of the nanoparticle and the base fluid, the suspended nanoparticles tend to sediment over time, the sedimentation rate can be high depending on the dispersion medium used (YU *et al.*, 2017).

Fig. (2.7) also shows that there are effective factors in the stability of nanoparticles, cited below, which have been examined by various researchers including the method of ultrasonication, dispersion speed, duration of dispersion, effect of the type of active surface of the material, temperature, effect of acidity, rotation speed, concentration of the active surface of the material, duration of ultrasonication and type of ultrasonication device (MURSHED *et al.*, 2005; XIE *et al.*, 2003; YANG *et al.*, 2020; YU and CHOI, 2003c).

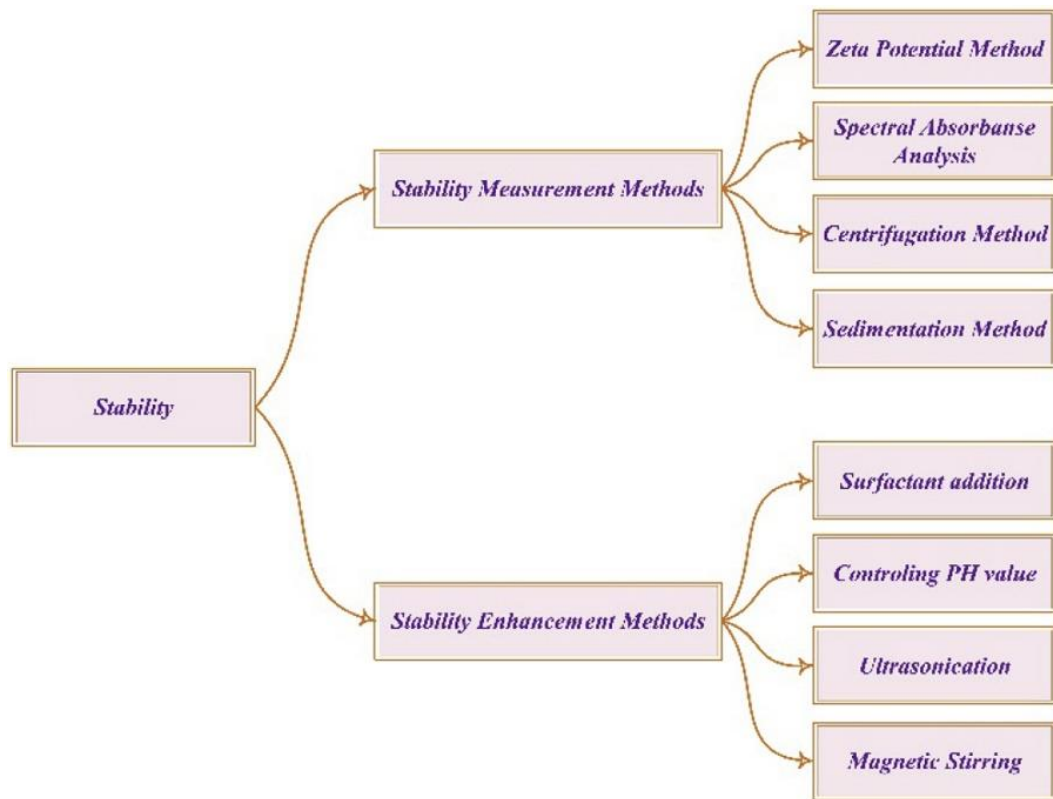


Figure 2.7 – Most used methods for measuring and improving the stability of nanofluids. Source: (YANG *et al.*, 2020).

Agglomeration of nanoparticles frequently occurs due to Van der Waals forces, electrical interaction forces in a double layer, etc., which substantially decrease the performance of nanofluids in thermal systems (HATAMI and JING, 2020). According to (OHMAE, 2008), particles suspended in a liquid medium are subjected to three types of forces: (a) gravitational forces which cause the nanoparticles to fall, (b) the viscosity of the liquid which reduces their speed of movement and (c) buoyancy, which can be opposed to gravitational forces, and in order to obtain a homogeneous and stable system, the size of the nanoparticles must be less than 100 nm. Applying the fundamental relations of dynamics, the expression for the sedimentation velocity in the permanent regime is obtained so that the velocity varies proportionally with the square of the nanoparticle radius, Eq. (2.39). However, nanoparticles with a larger radius will sediment faster than those with a smaller radius due to the flocculation process. Other effects may allow for better suspension stability, such as Brownian motion, which corresponds to the chaotic movement of nanoparticles due to liquid molecules colliding on their surface. Fig. (2.8a) shows the repulsive force between particles and its steric and electrostatic stability, Fig. (2.8b) shows the microscopic model of the model of nanoparticle Brownian motion.

$$V = \frac{2}{9} \cdot \frac{R^2}{\mu} \cdot (\rho - \rho') \cdot g \quad (2.39)$$

with, R the nanoparticle radius, μ the dynamic viscosity of the liquid, ρ the nanoparticle density and ρ' the liquid density.

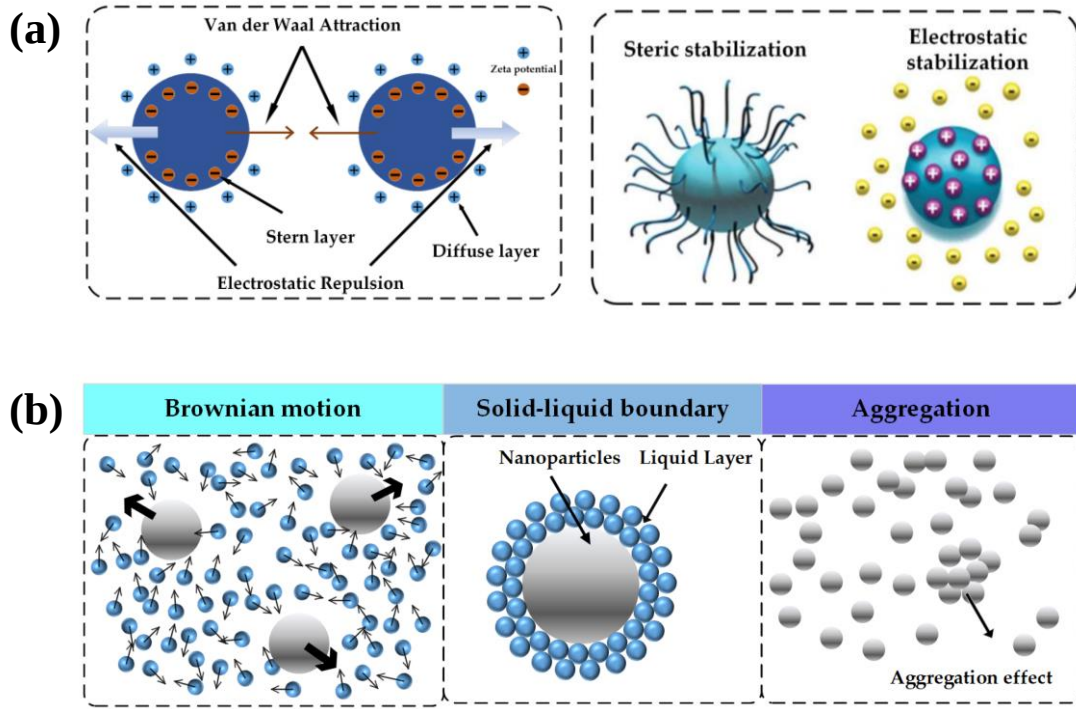


Figure 2.8 – (a) Van der Waals force and electrostatic repulsion and electrostatic stability and steric stability. (b) Brownian motion of the nanofluid, and the schematic diagram of the boundary layer and the aggregation effect. Adapted from: (CHU *et al.*, 2023).

Intermolecular interactions, described by Lennard-Jones forces, arise from steric repulsion at very short distances and Van der Waals attraction at short distances. Key factors enhancing the stability of nanofluids include ultrasonication, nanoparticle dispersion speed and duration in the base fluid, nanoparticle geometry, temperature, nanofluid acidity, rotational speed during synthesis, nanoparticle concentration, and the type and duration of ultrasonication equipment used (CHAKRABORTY and PANIGRAHI, 2020; ILYAS *et al.*, 2017; SETIA; GUPTA; WANCHOO, 2013; SHI *et al.*, 2021; YANG *et al.*, 2020; YU and XIE, 2012). Table 2.3 summarizes the parameters and preparation methods used in the experimental works found in the literature involving the flow of nanofluids undergoing a sudden change in geometry.

Table 2.3 – Some experimental setup details of nanofluid flow through sudden geometry change in recent literature.

Author	Nanofluid	Nanoparticle size (nm)	Nanoparticle concentration %	Dispersion technique	Sonication time	Surfactant
(KHERBEET <i>et al.</i> , 2014)**	Al ₂ O ₃ /Water SiO ₂ / Water	30	0 – 1 % vol.	Ultrasonic vibration	30 min for each 100 ml	Without surfactant
(AMIRI <i>et al.</i> , 2016)**	EGGNP / Water: Ethylene glycol (40:60)	-----	0.01 - 0.2 % wt.	Ball-milling	10 min	Without surfactant
(TOGUN <i>et al.</i> , 2017)**	Al ₂ O ₃ / Water	13	0 - 2 % vol.	Ultrasonic vibration	60 min	Without surfactant
(HILO <i>et al.</i> , 2020) ***	CuO / Ethylene glycol MgO / Ethylene glycol	40	1 - 5 % vol.	Magnetic hot plate stirring	1 hour	Without surfactant
(MONTAZER <i>et al.</i> , 2020a) ***	GNP / Distilled water	5-10	0.05 - 0.1 % wt.	Ultrasonic disrupter	40 min	Without surfactant
	MWCNT / Distilled water	20-1000	0.05 - 0.1 % wt.		40 min	
	SiO ₂ / Distilled water	10-20	0.05 - 0.2 % wt.		30 min	
	ZnO / Distilled water	<50	0.05 - 0.2 % wt.		60 min	
(ABDULRAZZAQ <i>et al.</i> , 2020a) **	Al ₂ O ₃ / Distilled water	12	0.5 – 2 % vol.	Ultrasonic vibration	60 min	Without surfactant
(YANG <i>et al.</i> , 2021) **	TiO ₂ / Distilled water	25	0.1 - 0.3 % vol.	Ultrasonic vibration	45 min	SDBS
	SiO ₂ / Distilled water					
	Al ₂ O ₃ / Distilled water					
(ABU TALIB and SALMAN, 2023) ***	βGa ₂ O ₃ / Water	30	0.01 – 0.04 % vol.	Ultrasonic disrupter	6 hours	Without surfactant

Source: Author's own.

** Numerical and experimental investigation; *** Experimental investigation

2.3 Flow geometry

Flows through a sudden axisymmetric contraction or expansion, in forward facing step (FFS) or backward facing step (BFS) channels and through channels with obstacles, create zones of separation and subsequent reattachment (KAZI and TOGUN, 2015). The separation and recirculation zones have a significant impact on the performance of heat exchangers, electronic cooling systems, automotive radiators, microchannels, circular ducts and many other heat exchange devices, which is considered in engineering designs. As a result, the reactor region mixes a considerable amount of low and high energy (SALMAN *et al.*, 2020). Studies on the heat transfer in nanofluids flow under sudden expansion or contraction, whether axisymmetric, in channels with forward facing step (FFS) or backward facing step (BFS) are quite limited for the laminar regime, and most of the work related to the subject has been carried out numerically. Most of the experimental research on the subject to date has been carried out exclusively in the turbulent or transition regime (ABU TALIB *et al.*, 2022; AMIRI *et al.*, 2016; HILO *et al.*, 2020; MONTAZER *et al.*, 2020b; TOGUN *et al.*, 2017).

2.3.1 Balance equations and boundary conditions

In the nanofluid flow in pipes with sudden expansion and/or contraction, the balance equations for the model for the permanent regime can be assumed with constant thermophysical properties, behavior of a Newtonian and incompressible fluid, no viscous transformations, natural convection, negligible thermal radiation and thrust effects (OZTOP and DAGTEKIN, 2003). Introducing the following dimensionless quantities:

$$\left. \begin{aligned} X = \frac{x}{d}, R = \frac{r_o}{d}, U = \frac{u}{U_m}, V = \frac{v}{U_m}, Re = \frac{U_m * d}{\nu} \\ \theta = \frac{T - T_c}{T_h - T_c}, Pr = \frac{\nu}{\alpha} \end{aligned} \right\} \quad (2.40)$$

The dimensionless forms of the balance equations in cylindrical coordinates, the continuity equation, momentum, and energy are obtained as:

Continuity

$$\left[\frac{\partial U}{\partial X} + \frac{\partial V}{\partial R} \right] = 0 \quad (2.41)$$

Momentum at X

$$\left[U \cdot \frac{\partial U}{\partial X} + V \cdot \frac{\partial U}{\partial R} \right] = -\frac{\partial P}{\partial X} + \frac{1}{Re} \cdot \left[\frac{\partial}{\partial X} \cdot \left(\frac{\partial U}{\partial X} \right) + \frac{\partial}{\partial X} \cdot \left(\frac{\partial U}{\partial R} \right) \right] \quad (2.42)$$

Momentum at R

$$\left[U \cdot \frac{\partial V}{\partial X} + V \cdot \frac{\partial V}{\partial R} \right] = -\frac{\partial P}{\partial R} + \frac{1}{Re} \cdot \left[\frac{\partial}{\partial X} \cdot \left(\frac{\partial V}{\partial X} \right) - \frac{V}{Re} + \frac{\partial}{\partial R} \cdot \left(\frac{\partial V}{\partial R} \right) \right] \quad (2.43)$$

Energy

$$\frac{\partial}{\partial R} \cdot \left[U \cdot \frac{\partial(R\theta)}{\partial X} + V \cdot \frac{\partial(R\theta)}{\partial R} \right] = \frac{1}{Re \cdot Pr} \cdot \left[\frac{\partial}{\partial X} \cdot \left(\frac{\partial \theta}{\partial X} \right) + \frac{\partial}{\partial X} \cdot \left(\frac{\partial \theta}{\partial R} \right) \right] \quad (2.44)$$

The local Nusselt number can be defined as:

$$Nu_x = \frac{h(x) \cdot d}{k} \quad (2.45)$$

where the local heat transfer coefficient and the average temperature of the volume can be defined as:

$$T_m = \int_0^{r_o} C_p \cdot \rho \cdot U(R) \cdot T \cdot R \cdot dR \quad (2.46)$$

$$h(x) = \frac{q(x)}{T_m(x) - T_h(x)} \quad (2.47)$$

The heat transfer rate $\frac{Q_s}{Q_o}$ can be calculated using the following equations:

$$Q_o = \dot{m} \cdot C_p \cdot (T_{mo} - T_c) \quad (2.48)$$

$$Q_s = \dot{m} \cdot C_p \cdot (T_{ms} - T_c) \quad (2.49)$$

Eq. (2.40) to Eq. (2.49) were obtained for a circular duct configuration with contraction-expansion-contraction in the numerical investigation proposed by (OZTOP and DAGTEKIN, 2003).

When an incompressible fluid flows through a sudden expansion, Fig. (2.9), the total and irreversible pressure drop can be found by applying the one-dimensional momentum equations and mechanical energy conservation equations (ROUL and DASH, 2011).

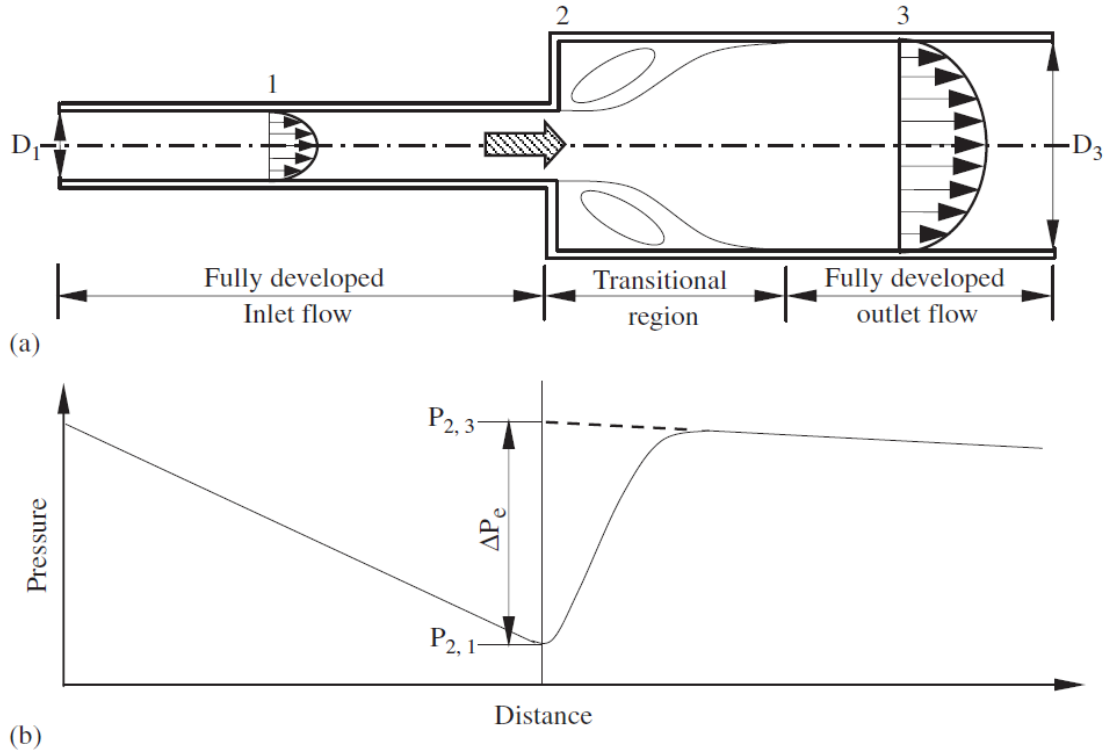


Figure 2.9 – (a) Idealized course of boundary streamlines and (b) pressure profile for a sudden expansion. Source: (ROUL and DASH, 2011).

$$\Delta P_e = P_{2,1} - P_{2,3} = \Delta P_{e,R} + \Delta P_{e,I} = \rho \cdot (u_1)^2 \cdot (\sigma^2 \cdot k_{d3} - \sigma \cdot k_{d1}) \quad (2.50)$$

$$\text{where } \sigma = \frac{A_1}{A_3}, \text{ and } k_d = \langle u^2 \rangle / \langle u \rangle^2 \quad (2.51)$$

$$\Delta P_{e,I} = K_e \cdot \rho \cdot \frac{\langle u_1 \rangle^2}{2} \quad (2.52)$$

$$\Delta P_{e,R} = -\frac{\langle u_1 \rangle^2}{2} \cdot \rho \cdot (1 - \sigma^2) \quad (2.53)$$

In single-phase flow through a sudden contraction, Fig. (2.10), up to the vena-contracta point C, the acceleration of the fluid is approximately isentropic, and the loss of mechanical energy occurs predominantly after the deceleration past to the vena-contracta point (ROUL and

DASH, 2011). The expansion from the vena-contracta point for the fully developed flow can be modeled as a flow through a sudden expansion (ABDELALL et al., 2005; CHALFI and GHIAASIAAN, 2008; KAYS, 1950).

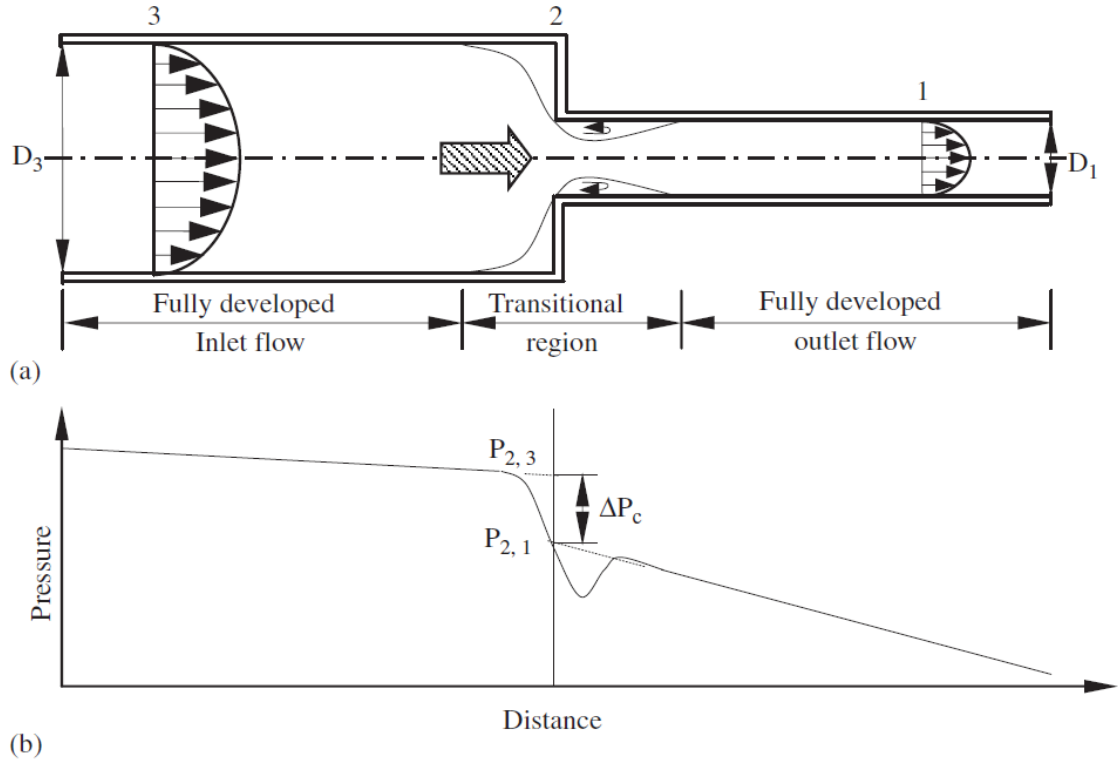


Figure 2.10 – (a) Idealized course of boundary streamlines and (b) pressure profile for a sudden contraction. Source: (ROUL and DASH, 2011a).

$$\Delta P_c = P_{2,3} - P_{2,1} = \Delta P_{c,R} + \Delta P_{c,I} = \frac{\langle u_1 \rangle^2}{2} \cdot \frac{1 - \beta_3 \cdot \sigma^2 \cdot C_{co}^2 - 2 \cdot C_{co} + 2 \cdot C_{co}^2 \cdot k_{d1}}{C_{co}^2} \quad (2.54)$$

were,

$$\beta = \frac{\langle u^3 \rangle}{\langle u \rangle^3} \quad (2.55)$$

$$C_{co} = \frac{A_{co}}{A_1} \quad (2.56)$$

For flow in channels with forward facing step (FFS) or backward facing step (BFS), the balance equations for laminar flow are obtained from the continuity equation, momentum and

energy solved in the Cartesian coordinate system (ALRASHED et al., 2018; BEHNAMPOUR et al., 2017; MAHMOUDI et al., 2012; RAISI et al., 2016).

Continuity:

$$\left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right] = 0 \quad (2.57)$$

Momentum equation at x:

$$\left[u \cdot \frac{\partial u}{\partial x} + v \cdot \frac{\partial u}{\partial y} \right] = -\frac{1}{\rho_{nf}} \cdot \frac{\partial P}{\partial x} + \nu_{nf} \cdot \left[\frac{\partial}{\partial x} \cdot \left(\frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \cdot \left(\frac{\partial u}{\partial y} \right) \right] \quad (2.58)$$

Momentum equation at y:

$$\left[u \cdot \frac{\partial v}{\partial x} + v \cdot \frac{\partial v}{\partial y} \right] = -\frac{1}{\rho_{nf}} \cdot \frac{\partial P}{\partial y} + \nu_{nf} \cdot \left[\frac{\partial}{\partial x} \cdot \left(\frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \cdot \left(\frac{\partial v}{\partial y} \right) \right] \quad (2.59)$$

Energy:

$$\left[u \cdot \frac{\partial T}{\partial x} + v \cdot \frac{\partial T}{\partial y} \right] = \frac{1}{c_{p_{nf}} \cdot \rho_{nf}} \cdot \left[\frac{\partial}{\partial x} \cdot \left(\kappa_{nf} \cdot \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \cdot \left(\kappa_{nf} \cdot \frac{\partial T}{\partial y} \right) \right] \quad (2.60)$$

Eq. (2.61) to Eq. (2.65) are used to calculate the Nusselt number, friction factor, pressure drop, pumping power and Reynolds number. The Nusselt number and friction factor are generally defined according to the heated wall (ALRASHED *et al.*, 2018).

$$Nu(x) = \frac{h \cdot D_h}{\kappa_f} = \frac{h \cdot H}{\kappa_f} \quad (2.61)$$

$$C_f = \frac{\tau_w}{\frac{1}{2} \cdot \rho \cdot u_{in}^2} \quad (2.62)$$

$$\Delta P = P_{out} - P_{in} \quad (2.63)$$

$$P_p = u_{in} \cdot A \cdot \Delta P \quad (2.64)$$

$$Re = \frac{u_{in} \cdot \rho \cdot H}{\mu} \quad (2.65)$$

2.3.2 Nanofluid flow under expansion

Flows under expansion are common in many industrial applications such as heat exchangers, combustion chambers and the cooling of electronic components. The phenomenon of flow separation and reattachment, which occurs close to sudden expansion, is a complex phenomenon that dictates the entire physics of the flow downstream of the stream (CHRISTOPHER *et al.*, 2012). The first work involving the flow of nanofluids under expansion was carried out by (ABU-NADA, 2008), who presented a BFS investigation using nanofluids composed of metallic nanoparticles and water as base fluid. It was reported by the author that for high Nusselt numbers inside the recirculation zone depends mainly on the thermophysical properties of the nanoparticles and is independent of the Reynolds number, however, it was observed that outside the recirculation zone both the values of the Reynolds number and the thermophysical properties of the nanofluid affect the value of the Nusselt number.

Fluid separation in annular channel flow occurs due to a change in the pressure gradient caused by an increase or decrease in the cross-sectional area of the annular channel (TOGUN *et al.*, 2017). Similarly, for flow in forward-facing step channels (FFS) and backward-facing step channels (BFS), fluid separation with subsequent reattachment occurs when the geometry is pressurized or expands abruptly. (SALMAN *et al.*, 2020). This phenomenon plays an important role in the design of many engineering applications that require heating or cooling operations (KHERBEET *et al.*, 2015).

The separation zone is accompanied by eddy structures that affect the heat transfer performance of the nanofluid, as observed by several researchers in numerical and experimental investigations (ABDULRAZZAQ *et al.*, 2020b; DEHGHAN *et al.*, 2023; KIMOUCHE *et al.*, 2017; KLAZLY and BOGNAR, 2022; NAGARAJAN and SOMA SUNDARAM, 2024; WU and KUMAR, 2022). (HILO *et al.*, 2020) experimentally investigated the heat transfer by forced convection and the friction factor in the flow of nanofluids in channels with BFS with ER equal to 2, the authors reported that the heat transfer increases with the increase in the volumetric concentration of the nanoparticles, where the Nusselt number increased by 11 % at a volume concentration of 0.05 % of CuO and MgO compared to pure ethylene glycol (EG), and the friction factor increased by approximately 15 % with a Reynolds number of 5000 and volume concentrations of 0.01 and 0.03.

(AL-ASWADI *et al.*, 2010) numerically investigated the laminar flow under forced convection of different nanofluids in a horizontal channel with BFS. The authors reported that the recirculation area and the reattachment length increase with increasing Reynolds number.

In addition, it was inferred that nanofluids with low-density nanoparticles such as SiO_2 have a higher velocity than those with high-density nanoparticles such as Au. (CHRISTOPHER *et al.*, 2012) investigated the laminar flow of nanofluids under sudden expansion in a parallel plate channel. The authors reported that increasing the Reynolds number results in a peak Nusselt number near the reattachment zone and low Nusselt values downstream, since with increasing recirculation Nusselt is decreased.

(KHERBEET *et al.*, 2015; KHERBEET *et al.*, 2012) respectively numerically and experimentally investigated the effects of laminar flow of nanofluids in microscale flows in channels with BFS and in channels with FFS. The numerical results revealed that no recirculation zone was observed in the flow of nanofluids for the step of $0.48 \mu\text{m}$. The experimental results revealed that in comparison with the flows in channels with BFS under similar boundary conditions, the flows in channels with FFS showed a higher friction factor due to the higher pressure drop in this geometry. It was also reported by the authors that the concentration of 0.01 % in volume for the nanofluid produced $\text{SiO}_2/\text{Water}$ showed the highest value of the Nusselt number. (NATH and KRISHNAN, 2019a) numerically investigated the convection heat transfer and mass transfer in the flow in a BFS channel containing the Cu/water nanofluid. The authors observed that with an increase in the volume concentration of the nanoparticle, the reattachment length obtained for the flow also increases, this being pronounced with an increase in the Prandtl number from 1.76 to 6.2. The maximum Nusselt increase reported for the nanoparticle was 77 % in relation to the base fluid, and it was also reported that the presence of the nanoparticle in the base fluid slows down the convective mass transfer in it.

(TOGUN *et al.*, 2014b) numerically investigated the heat transfer of the Cu/Water nanofluid for the laminar and turbulent regimes under a BFS channel flow. The authors reported that the volume concentration of the nanofluid causes an increase in the Nusselt number in both the laminar and turbulent regimes, with the effect of expansion being observed downstream of the inlet region where the peak in the Nusselt number profile was, according to the authors, caused by the increase in heat energy transfer due to the recirculation generated. (GEDIK *et al.*, 2015) numerically investigated forced convection in channels with sudden expansion. The nanofluid considered in the problem was $\text{Al}_2\text{O}_3/\text{Water}$, where the largest increases in the convective heat energy transfer coefficient, h , calculated were 24.2 % for 2 vol.% of Al_2O_3 and 51 % for 4 vol. % of Al_2O_3 in relation to the base fluid (water). (ACAR, 2019a) numerically investigated the heat transfer in the nanofluid flow under constant thermal energy flow in

channels with sudden expansion. The author simulated various nanofluids with different concentrations, using water as the base fluid. The author reported that the greatest increase in the heat energy transfer coefficient was obtained with the $\text{Al}_2\text{O}_3/\text{Water}$ nanofluid for a nanoparticle volume concentration of 2.0 %, the observed increase being approximately 5.40 %.

(HESHMATI *et al.*, 2014) investigated heat transfer with mixed convection in BFS channels with different slit-like deflections at the top of the channel wall using different nanofluids with different volume concentrations. Among all the nanofluids analyzed, SiO_2 was the one with the highest value for the Nusselt number, but it also had the highest values for pressure drop and friction coefficient. (TOGUN, 2016) numerically investigated the heat transfer of CuO/water nanofluid flowing downstream with and without an obstacle. It was reported that the maximum increase in heat transfer was approximately 22 % for flow in BFS channels with a 4.5 mm obstacle compared to flow without obstacles. It was also observed that the recirculation zone increases with increasing obstacle size on the channel wall, which affects the thermal performance of the nanofluid. (MA *et al.*, 2020) presented a numerical simulation for heat transfer of $\text{MWCNT-Fe}_3\text{O}_4/\text{Water}$ hybrid nanofluid flowing in a channel with upstream and downstream flows having a fixed obstacle at the top of the channel wall. The authors reported that the obstacle at the top of the wall has a significant effect on the flow pattern and on the heat transfer characteristics. The authors reported that when the length of the obstacle increases, the recirculation zone downstream of the flow in channels with BFS decreases and the rate of thermal energy transfer increases.

(POUR and NASSAB, 2012) numerically investigated the laminar flow under forced convection of channel nanofluids with BFS subject to the overflow condition. The authors simulated various nanoparticles with different volumetric concentrations in water as the base fluid. The authors reported that the Nusselt number increased with increasing volumetric concentration, with the largest reported increase being 80 % with the Cu nanoparticle compared to water. (QI *et al.*, 2020) studied a computational model of a BFS channel flow in the turbulent regime to investigate the heat transfer of the $\text{Cu-Ni}/\text{water}$ hybrid nanofluid. The authors focused on the influence of the number of steps and the expansion radius of the channel on the flow and heat energy transfer of the nanofluid. It was reported that increasing the number of steps causes an increase in the Nusselt number downstream of the step and results in a peak in the position of the Nusselt number upstream. The expansion radius was defined as the ratio between the channel and the step height as shown in Fig. (2.11), where the upstream length, downstream

length, inlet step height, step height and total channel height are defined respectively by L_1 , L_2 , H_1 , S and H_2 .

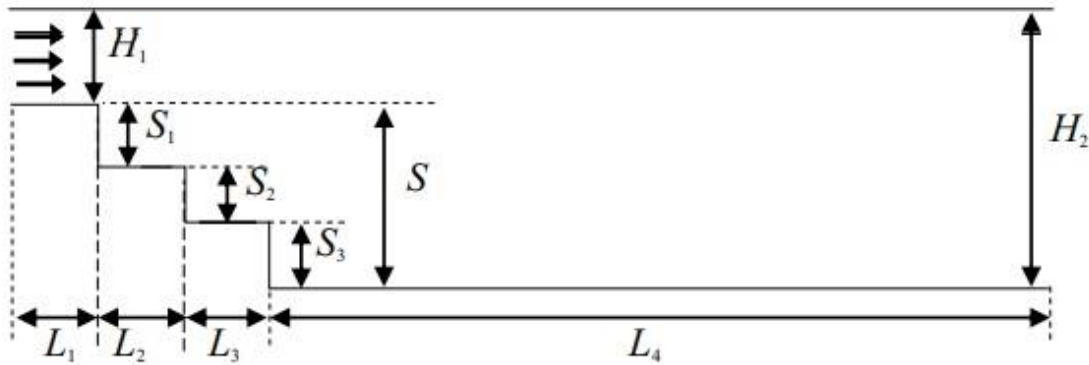


Figure 2.11 – Schematic diagram of the calculation of the flow area with triple descent (BFS). Source: (QI *et al.*, 2020).

(TOGUN *et al.*, 2016b) numerically investigated heat transfer in the flow of Al_2O_3 /water nanofluid through an annular pipe with sudden expansion, in which the outer cylinder of the downstream section is uniformly heated while the outer cylinder of the upstream section and the entire inner cylinder are adiabatic. The authors reported that the heat transfer coefficient increases with increasing Al_2O_3 nanoparticle volume concentration and Reynolds number. The simulation results reported by the authors also showed that the separation region formed after sudden expansion considerably affected the heat transfer coefficient on the surface. (KIMOUCHE *et al.*, 2017) numerically investigated the turbulent forced convection of Ag/Water, Cu/Water, CuO/Water and Al_2O_3 /Water nanofluids through an abrupt axisymmetric expansion. The authors proposed two correlations for the average Nusselt number, the first correlation is a function of the Reynolds number, volumetric concentration and ratio of the densities of the solid nanoparticle and the base fluid, the second relates the Reynolds number, volumetric concentration and ratio of the thermal conductivities of the solid nanoparticle and the base fluid. The highest values for the average Nusselt number were obtained by the Al_2O_3 /Water nanofluid. (NOURI *et al.*, 2018) investigated the entropy generation of CuO/water nanofluid flowing through a spherical thermal energy source that is installed inside a cylindrical channel with sudden expansion and contraction. The authors proposed a correlation for the Nusselt number which is a function of the Reynolds number, the Prandtl number and the blockage radius. The authors reported that increasing the blocking radius, increasing the diameter of the thermal energy source and reducing the diameter of the nanoparticle decreases

entropy generation, while increasing the volume concentration of the nanoparticle and increasing the temperature at the source causes an increase in the Nusselt number and entropy generation.

(ALIZADEH *et al.*, 2020a) numerically investigated the effect of nanofluids flowing as jets in heat transfer processes under forced convection, within channels with turbulent BFS in the presence of a magnetic field. The CuO/water nanofluid was simulated by the author, where increasing the nanoparticle volume concentration increased the thermal conductivity and heat transfer coefficient of the base fluid. The author also reported that the imposed magnetic field, as well as high Reynolds numbers, have a great influence on the performance of equipment that includes thermal exchange and fluid flow. (SELIMEFENDIGIL and ÖZTOP, 2020) numerically investigated the effects of local curvature for laminar forced convection flows for stratified channels involving nanofluids (SWCNT/Water and MWCNT/Water) and porous layers with sudden area expansion considering magnetic field effects. The authors observed that the average heat transfer rate increases with high values of the Reynolds number, the magnetic field strength and the permeability of the porous region. The maximum Nuselt number increases reported were approximately 12.86 % and 22.48 % for the SWCNT/Water and MWCNT/Water nanofluids respectively.

(TOGUN *et al.*, 2017) investigated numerically and experimentally the heat transfer in the nanofluids flow on turbulent regime in a concentric annular pipe with different sudden expansion ratios, as shown in the diagram in Fig. (2.12). The authors used the nanofluid Al_2O_3 /Water in the material experiment to validate the results of the computational model. For an expansion ratio of 2, a volumetric concentration of 2 %, and a Reynolds number of 50000, the average increase in the heat energy transfer coefficient for the Al_2O_3 /Water nanofluid was approximately 6.59 % for the material experiment and approximately 6.48 % for the computational experiment, indicating a good match between the numerical and experimental results. (HILO *et al.*, 2020) experimentally investigated the convective heat transfer to the flow in backward facing step channels (BFS) of nanofluids in a suddenly expanding channel with uniform heat flux, Fig. (2.13). The authors reported an 11 % increase in the Nusselt number for the CuO/Ethylene Glycol (EG) nanofluid with a nanoparticle vulumetric concentration of 5 % in relation to the base fluid (EG). (MONTAZER *et al.*, 2020b) experimentally investigated heat transfer with forced convection on turbulent regime for the nanofluids flow in a heat exchanger with axisymmetric sudden expansion, Fig. (2.14). The authors presented two correlations for the local Nusselt number, which increased with increasing axial radii in all the cases

investigated. The authors reported that, among all the nanofluids investigated, those with carbon-based nanoparticles had a greater effect on increasing thermal energy transfer (33.7 % and 16.7 % for F-GNP functionalized graphene nanoplatelets and MWCNT multi-walled carbon nanotubes respectively at a mass concentration of 0.1 %) downstream of sudden expansion in the pipe.

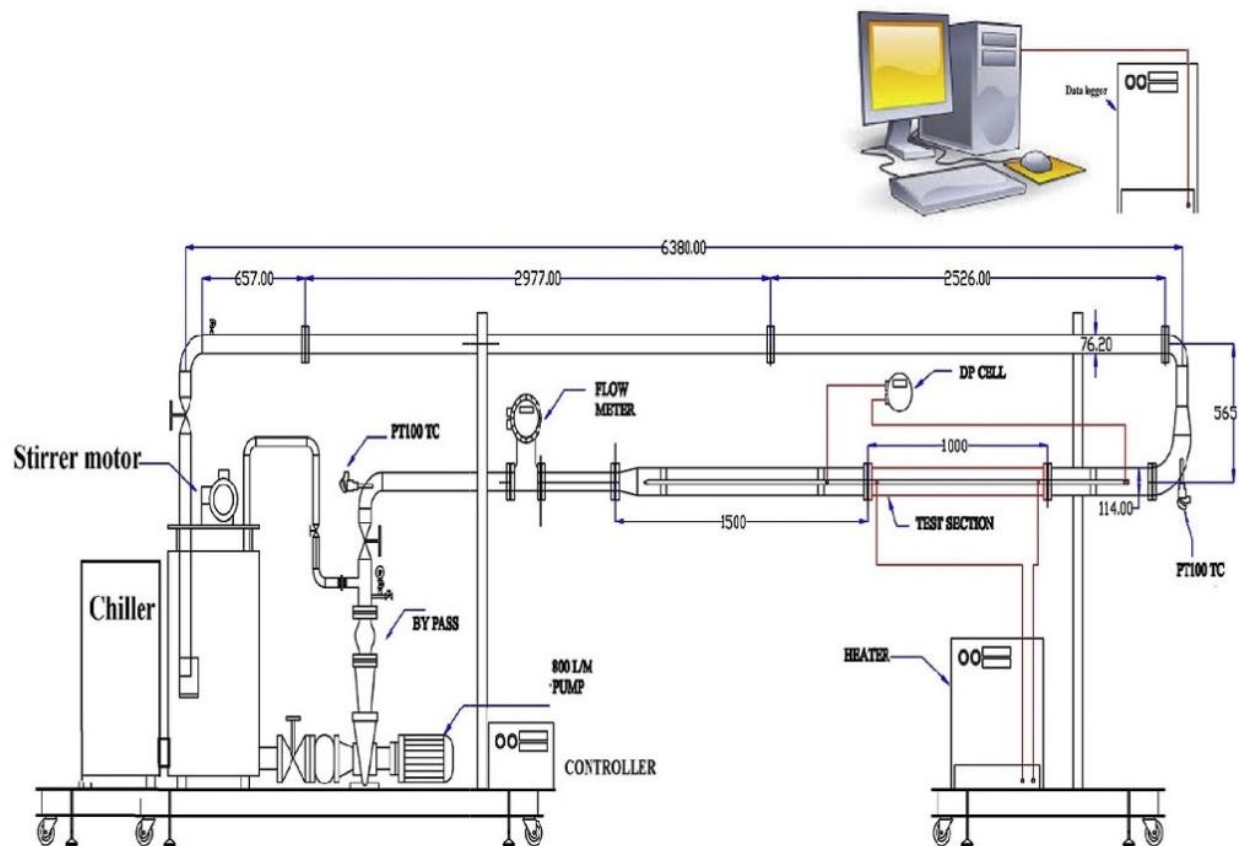


Figure 2.12 – Schematic diagram of the experimental apparatus used by (TOGUN; et al., 2017).

(WU and KUMAR, 2022) conducted a numerical investigation of $\text{Al}_2\text{O}_3/\text{Water}$ nanofluid flow over a BFS with two expansion ratios (1.94 and 3.5). The results presented by the authors show that the friction factor decrease with Reynolds number and volume fraction, and the maximum heat transfer obtained was 63.11 % in relation to base fluid with $\text{ER} = 1.94$. (ABU TALIB et al., 2022) and (ABU TALIB and SALMAN, 2023) experimental investigated the heat transfer of CuO/Water and $\beta\text{Ga}_2\text{O}_3/\text{Water}$ nanofluid respectively flow over a microscale BFS at high Reynolds number, Fig. (2.15). According to the authors heat transfer increases with increment of volume fraction and Reynolds number. The maximum increment of Nusselt number for samples with 4 % vol. reported was 13.04 % for CuO and 19.2 % for $\beta\text{Ga}_2\text{O}_3$ in

relation to the base fluid. (DEHGHAN *et al.*, 2023) investigated the numerical heat transfer of GO/Water nanofluid over double BFS microchannel. To improve the thermal performance a triangular obstacle is placed at the top of the first and second steps with different nanoparticle fractions. According to the author using the triangular obstacle a improvement on heat transfer of 12.3 % using CuO with 4 % vol. in relation to the base fluid is achieved. (RANA *et al.*, 2022) conducted a numerical simulation of CuO/Water nanofluid flowing in a BFS micro-scale to investigate its thermohydraulic performance. The results presented by the authors shown that the enhancement of nanoparticle fraction leads to an increase of Nusselt number and a increse of friction factor with the increase of Reynolds number. As the obstacle is high, the Nusselt number increases and the primary recirculation zone behind the step decrease, however the secondary recirculation zone behind the obstacle tends to increase. (KARAMI *et al.*, 2023) conducted a numerical simulation of turbulent nanofluid flor under forced convection in a grooved cylinder. The authors focused on the influence of groove depth, groove position and CuO nanoparticle on heat transfer. According to the authors the use of nanofluids in grooved tube increase the heat transfer, however the use of CuO/water nanofluid at high Reynolds number reduces the efficiency. (NAGARAJAN and SOMA SUNDARAM, 2024) conducted a numerical study on the impact of appendages on heat transfer enhancement and fluid flow characteristics over a backward-facing step. The study examined the effects of Reynolds number and various appendage orientations on convective heat transfer, using water as the working fluid. The simulations revealed that the average Nusselt number increased with higher Reynolds numbers and the introduction of appendages enhanced the Nusselt number. (TOGUN *et al.*, 2024) numerically investigated heat transfer enhancement in a two-dimensional channel with backward-facing steps (BFS) and unique square-rectangular ribs. The authors analyzed the effects of rib geometry, including adjustable height and width, and uniform placement on the heated bottom wall. The results presented by the authors indicated that geometric parameters significantly influence thermo-fluid flow and heat transfer. Fewer ribs with moderate height and width and closer spacing provided superior thermal performance, while fewer ribs with greater height and width and wider spacing resulted in the worst thermal performance.

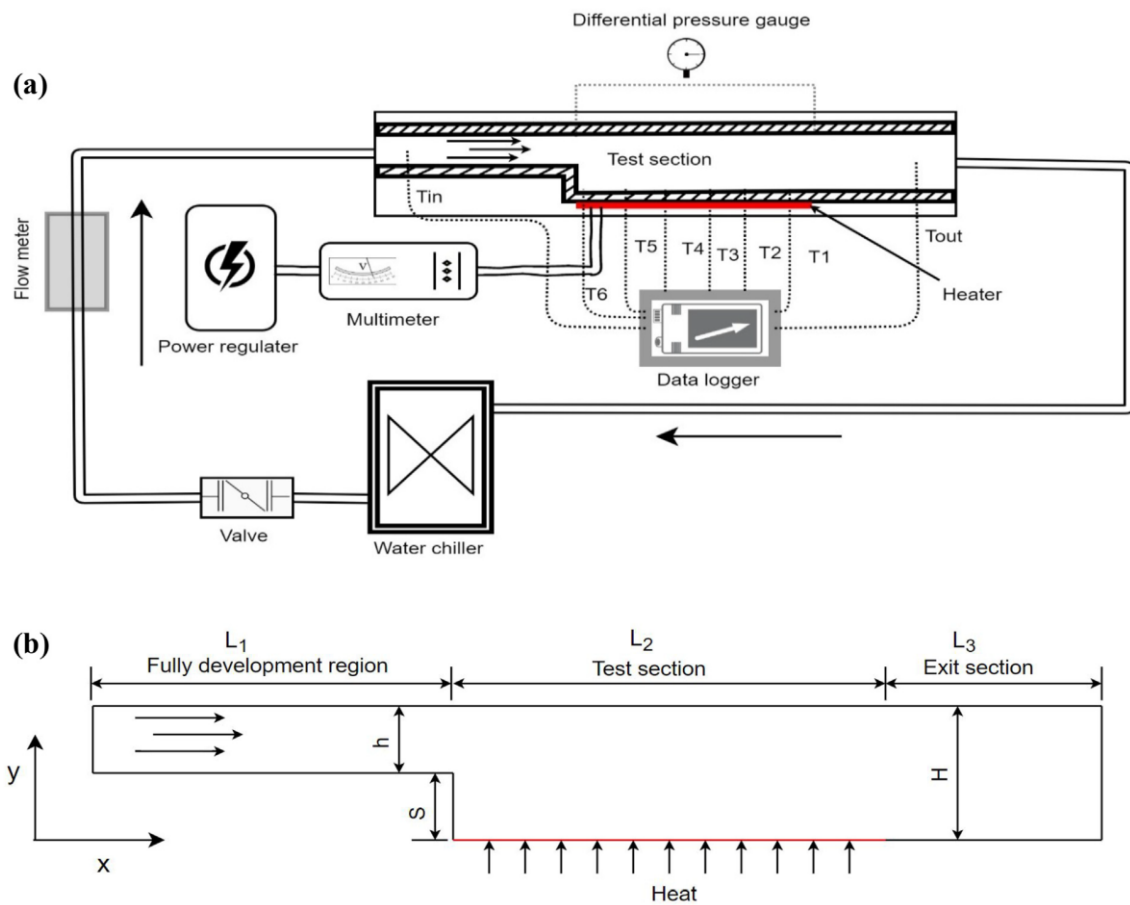


Figure 2.13 – (a) Schematic representation of the experimental apparatus, (b) configuration of the tested channel used by (HILO *et al.*, 2020).

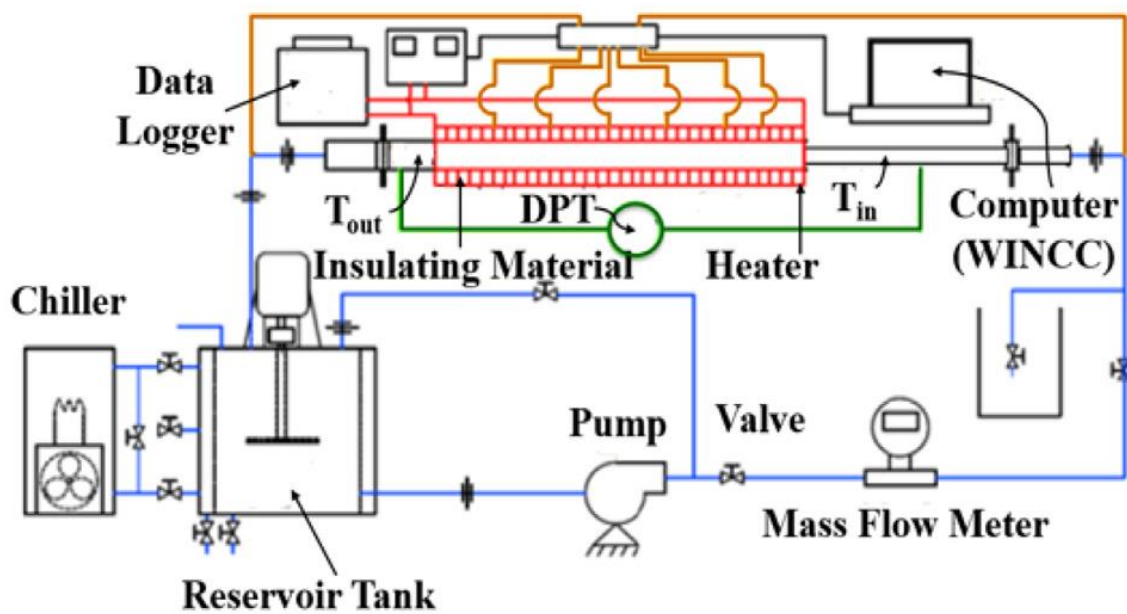


Figure 2.14 – Schematic diagram of the test section used by (MONTAZER *et al.*, 2020b).

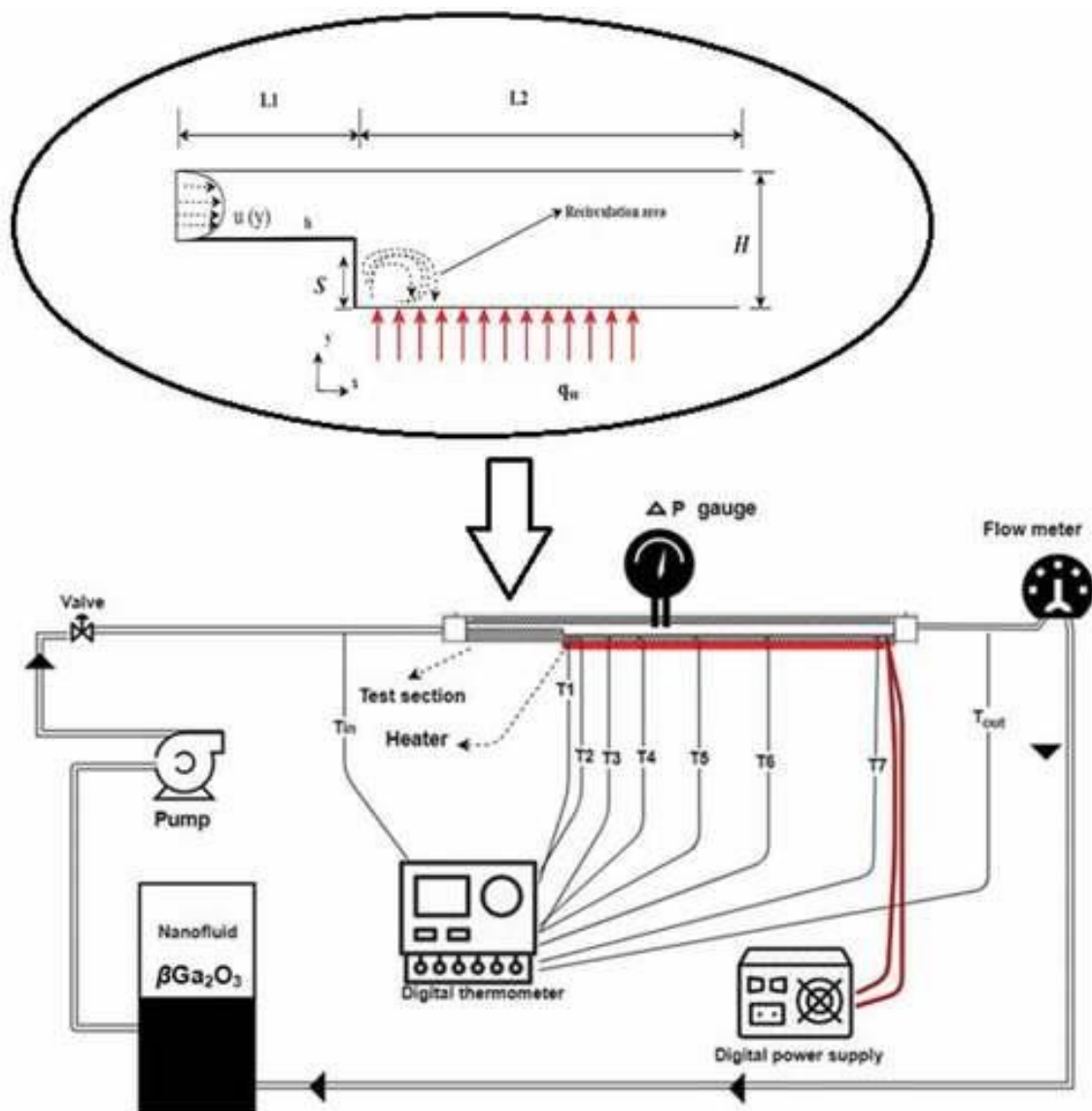


Figure 2.15 – MBFS schematic diagram and experimental setup used by (ABU TALIB and SALMAN, 2023).

As previously mentioned, works on heat transfer in nanofluid flow considering expansion effects is quite limited, with the vast majority of work on the subject being carried out numerically. The key results of the main studies on the subject are shown in Table 2.4, where the researchers focused mainly on analyzing the Nusselt number and the heat transfer coefficient in flows under expansion of different nanofluids.

Table 2.4 – Summary of the state-of-the-art involving heat transfer in nanofluid flow under expansion.

Author	Nanofluid	Nanoparticle concentration %	Expansion ratio	Findings
(ABU-NADA, 2008)*	Cu / Water Ag / Water CuO / Water Al ₂ O ₃ / Water TiO ₂ / Water	0.05 - 0.2 % vol.	2	For Cu: Nu ↑ 25.57 % For Ag: Nu ↑ 26.52 % For CuO: Nu ↑ 21.68 % For Al ₂ O ₃ : Nu ↑ 22.55 % For TiO ₂ : Nu ↑ 19.84 %
(SANTOSH CHRISTOPHER <i>et al.</i> , 2012)*	Ag / Water Cu / Water Al ₂ O ₃ / Water SiO ₂ / Water	0 - 0.2 % vol.	2	For Ag: Nu ↑ 43.15 % For Cu: Nu ↑ 42.07 % For Al ₂ O ₃ : Nu ↑ 40.71 % For SiO ₂ : Nu ↑ 17.35 %
(POUR AND NASSAB, 2012)*	Ag / Water Cu / Water Al ₂ O ₃ / Water SiO ₂ / Water	0.05 – 0.2 % vol.	2	For Cu : Nu ↑ 80 %
(KHERBEET <i>et al.</i> , 2012)*	Al ₂ O ₃ / Water CuO / Water SiO ₂ / Water ZnO / Water	1 – 4 % vol.	2	The nanofluid of SiO ₂ nanoparticles is observed to have the highest Nusselt number value

Source: Author's own.

* Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

Table 2.4 – (continued).

Author	Nanofluid	Nanoparticle concentration %	Expansion ratio	Findings
(TOGUN <i>et al.</i> , 2014d)*	Cu / Water	0 – 4 % vol.	2	For Cu: Nu ↑ 26.49
(KANNA <i>et al.</i> , 2015)*	Ag / Water Cu / Water Al ₂ O ₃ / Water SiO ₂ / Water	0.2 % vol.	2	For Ag: Nu ↑ 37.02 % For Cu: Nu ↑ 37.16 % For Al ₂ O ₃ : Nu ↑ 38.07 % For SiO ₂ : Nu ↑ 16.87 %
(AMIRI <i>et al.</i> , 2016)**	EGGNP / Water: Ethylene glycol (40: 60)	0.01 - 0.2 % wt.	2	For EGGNP: h ↑ 25.88 % Nu ↑ 26.05 %
(TOGUN <i>et al.</i> , 2016b)*	Al ₂ O ₃ / Water	1 – 2 % vol.	1.25; 1.67; 2	For Al ₂ O ₃ : h ↑ 7.31 %
(TOGUN, 2016)*	CuO / Water	1 - 4 % vol.	6; 3.2; 2.13	For CuO: Nu ↑ 6.65 %

Source: Author's own.

* Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

Table 2.4 – (continued).

Author	Nanofluid	Nanoparticle concentration %	Expansion ratio	Findings
KIMOUCHE et al., 2017)*	Ag / Water Cu / Water CuO / Water Al ₂ O ₃ / Water	0 - 0.2 % vol.	1.53	For Cu: Nu ↑ 12.39 % For CuO: Nu ↑ 16.37 % For Al ₂ O ₃ : Nu ↑ 22.47 % For Ag: Nu ↑ 9.51 %
(TOGUN et al., 2017)**	Al ₂ O ₃ / Water TiO ₂ / Water CuO / Water	0 - 2 % vol.	1.25; 1.67; 2	For Al ₂ O ₃ : h ↑ 12.3 % For TiO ₂ : h ↑ 10.7 % For CuO: h ↑ 8.6 %
(NOURI et al., 2018)*	CuO / Water	1 - 6 % vol.	2	For CuO: Nu ↑ 26.79 %
(ACAR, 2019b)*	Al ₂ O ₃ / Water TiO ₂ / Water SiO ₂ / Water ZnO / Water Cu / Water	0.5 - 2 % vol.	2	Al ₂ O ₃ : h ↑ 4.16 % TiO ₂ : h ↑ 3.42 % SiO ₂ : h ↑ 1.42 % ZnO: h ↑ 3.08 % Cu: h ↑ 2.74 %
(NATH and KRISHNAN, 2019b)*	Cu / Water	0 - 0.2 % vol.	2	For Cu: Nu ↑ 77 %

Source: Author's own.

* Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

Table 2.4 – (continued).

Author	Nanofluid	Nanoparticle concentration %	Expansion ratio	Findings
(NATH and KRISHNAN, 2019c)*	Cu / Water	0 - 0.2 % vol.	2	For Cu: Nu ↑ 77 %
(HILO <i>et al.</i> , 2020)***	CuO / Ethylene glycol MgO / Ethylene glycol	1 - 5 % vol.	2	For CuO: Nu ↑ 4.18 % For MgO: Nu ↑ 2.72 %
(MONTAZER <i>et al.</i> , 2020b)***	GNP / Distilled water	0.05 - 0.1 % wt.	2	For GNP: h ↑ 33.7 %
	MWCNT / Distilled water	0.05 - 0.1 % wt.		For MWCNT: h ↑ 33.7 %
	SiO ₂ / Distilled water	0.05 - 0.2 % wt.		For ZnO: h ↑ 14.35 %
	ZnO / Distilled water	0.05 - 0.2 % wt.		For SiO ₂ : h ↑ 10.1 %
(MA <i>et al.</i> , 2020)*	MWCNT - Fe ₃ O ₄ / Water	0 - 0.3 % vol.	2	For MWCNT - Fe ₃ O ₄ : Nu ↑ 59.26 %
(ALIZADEH <i>et al.</i> , 2020a)*	CuO / Water	1 - 3 % vol.	2	For CuO: Nu ↑ 20.17 %
(QI <i>et al.</i> , 2021)*	Cu - Ni / Water	5 % wt.	1.33 - 3	For Cu-Ni: Nu ↑ 8.7 %
(SAFAEI <i>et al.</i> , 2021)*	Cu / Water	2 – 4 % vol.	2 (microtubes) with expansion angles: 30°, 45°, 60° and 90°	For Cu: HTC ↑ 28.1 %

Source: Author's own

* Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

Table 2.4 – (continued).

Author	Nanofluid	Nanoparticle concentration %	Expansion ratio	Findings
(YANG <i>et al.</i> , 2021)**	TiO ₂ / Deionized water SiO ₂ / Deionized water Al ₂ O ₃ / Deionized water	0.1 - 0.3 % vol.	2 (microchannels)	For TiO ₂ : Nu ↑ 28 % For SiO ₂ : Nu ↑ 25 % For Al ₂ O ₃ : Nu ↑ 48
(TOGUN <i>et al.</i> , 2021)*	Al ₂ O ₃ - Cu / Water	0.1 – 2 % vol.	Case 1: 5:1:1 (em cm) Case 2: 5:2:1 (em cm) Case 3: 5:1:2 (em cm)	For Al ₂ O ₃ : h ↑ 2 %
(SAFAEI <i>et al.</i> , 2021b)*	Cu / Water	0 - 4 % vol.	2 (microtubes) with expansion angles: 30°, 45°, 60° and 90°	For Cu: HTC ↑ 28.1 %
(TOGUN, 2021)*	Fe ₃ O ₄ / Water	0.5 – 2 % vol.	1.25; 1.67; 2	Sudden increases in Nusselt number were observed after abrupt enlargement.
(KLAZLY and BOGNAR, 2022)*	Al ₂ O ₃ / Water TiO ₂ / Water	1 - 4 % vol.	1.67 (BFS)	For Al ₂ O ₃ : h ↑ 18.68 % For TiO ₂ : h ↑ 13.52 %
(SAHA and DAS, 2022)*	Al ₂ O ₃ / Water	0 - 4 % vol.	1-30	For Al ₂ O ₃ : Nu ↑ 146 %
(GÜRSOY <i>et al.</i> , 2022)*	Magnetite/Water	1 - 2 % vol.	2.5 and 2	For Magnetite: Nu ↑ 3.34 %
(WU and KUMAR, 2022)*	Al ₂ O ₃ / Water	0 - 5 % vol.	1.94; 3.5 (BFS)	For Al ₂ O ₃ : h ↑ 63.11 %

Source: Author's own.

* Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

Table 2.4 – (continued).

Author	Nanofluid	Nanoparticle concentration %	Expansion ratio	Findings
(ABU TALIB <i>et al.</i> , 2022)*	CuO/Water	0 - 4 % vol	2	For CuO: Nu ↑ 13.04 %
(RANA <i>et al.</i> , 2022)*	CuO/Water	0 – 5 % vol.	1.94	For CuO: Nu ↑ 164 %
(ABU TALIB and SALMAN, 2023)**	β Ga ₂ O ₃ / Water	1 – 4 % vol.	2 (MBFS)	β Ga ₂ O ₃ : Nu ↑ 19.2 %
(DEHGHAN <i>et al.</i> , 2023)*	GO/Water	2 - 4 % vol.	2	For GO: Nu ↑ 12.7 %; h ↑ 12.3 %
(KARAMI <i>et al.</i> , 2023)*	CuO / Water	1 – 4 % vol.	1.1 and 1.2	For CuO: Nu ↑ 110 - 160 %
(PAZARLIOĞLU <i>et al.</i> , 2024)*	Ag-MgO/Water	0 – 2 % vol.	2.5 with expansion angles: 30°, 45°, 60° and 90	For Ag – MgO: Nu ↑ 20 %
(GÜRSOY <i>et al.</i> , 2024)*	Al ₂ O ₃ /Water	1 % vol.	2.5 with expansion angles: 30°, 45°, 60° and 90	For Al ₂ O ₃ ↑ 12.16 %

Source: Author's own.

* Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

2.3.3 Nanofluid flow under contraction

Conduits with expansion or contraction are used in many engineering applications such as combustion chambers, heat exchangers, electronic equipment, and power generation systems, and in many cases expansion or contraction in conduits is caused by BFS or FFS respectively (ATASHAFROOZ *et al.*, 2019). Recirculation and flow separation due to sudden contraction in closed conduits, FFS and BFS can be considered good options for increasing the performance of thermal systems (SAFAEI, 2015).

(SAFAEI *et al.*, 2014) numerically investigated the heat transfer under forced convection in the turbulent flow of the FMWCNT/water nanofluid in FFS, as shown in Fig. (2.16), where the geometric dimensions are: height of 2.5 cm at the inlet, upstream length (X_i) of 150 cm, downstream length (X_e) of 200 cm and 1.25 cm height at the channel outlet for a contraction radius of 2. The authors studied the effects of nanoparticle concentration, heat flux, contraction, and turbulence on the thermohydraulic behavior of the nanofluid. The authors reported that there was a substantial increase in the heat transfer coefficient after contraction for all the cases analyzed. (KHERBEET *et al.*, 2015) investigated numerically and experimentally the characteristics of heat transfer in the horizontal flow of nanofluids in microchannels with forward facing step (MFFS). The authors considered two types of nanofluids, SiO₂/Water and Al₂O₃/Water as well as pure water. They reported from the experimental results that, compared to pure water, the greatest increase in the Nusselt number was 30.6 % for the SiO₂/Water nanofluid with a volume concentration of 1 %.

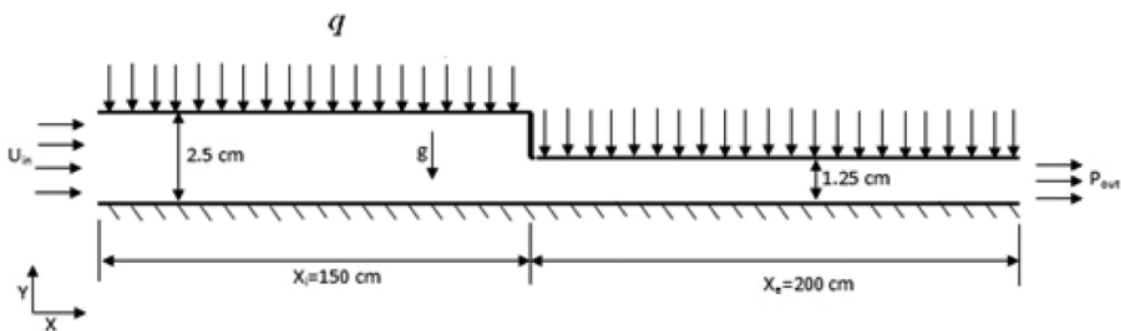


Figure 2.16 – Schematical configuration analyzed, with heat flux range of W/m^2 to 10000 W/m^2 . Source: (SAFAEI *et al.*, 2014).

(TOGUN *et al.*, 2015) numerically investigated the heat transfer of flow in the turbulent regime of the nanofluids Al₂O₃/Water and CuO/Water with different volume concentrations in channel flow with double forward-facing step (double FFS) in a horizontal channel. The authors

reported that the Nusselt number increases with increasing Reynolds number and with the volume concentration of the nanofluid. It was also observed that increasing the step height amplifies the heat transfer rate due to the increase in the flow recirculation region. (TOGUN *et al.*, 2021) numerically investigated the heat transfer in the flow of hybrid nanofluid $\text{Al}_2\text{O}_3\text{-Cu/Water}$ on turbulent regime for vertical FFS flows. Different step sizes were adopted for three cases in FFS flows with sudden contraction of the nanofluid for different volume concentrations. The authors observed that increasing the Reynolds number leads to an increase in the local heat transfer coefficient, with the maximum increase reported for the hybrid nanofluid at 2 vol.%.

(ALRASHED *et al.*, 2018) numerically investigated the laminar flow and heat transfer of the FMWCNT/water (functionalized multi-walled carbon nanotube/water) nanofluid in a BFS with sudden contraction. The authors reported that, in different parts of the channel, reducing the flow velocity causes a reduction in the friction coefficient, pressure drop and heat transfer coefficient.

(MOOSAVI *et al.*, 2021) numerically investigated the turbulent flow of $\text{Al}_2\text{O}_3\text{/Water}$ and CuO/Water nanofluids under forced convection in FFS, with a sudden step inclination of $20^\circ \leq \theta \leq 80^\circ$, with sudden contraction of the nanofluids for different volume concentrations. The authors reported that increasing the angle of inclination of the sudden step increases the heat transfer due to the increase in the recirculation zone, the increase in flow velocity and temperature fluctuations respectively. The highest values reported for the increase on heat transfer were approximately 26 % and 19 % for the $\text{Al}_2\text{O}_3\text{/Water}$ and CuO/Water nanofluids respectively, compared to the base fluid.

(ABDULRAZZAQ *et al.*, 2020c) numerically simulated the flow of the $\text{TiO}_2\text{/Water}$ nanofluid in the annular space of two concentric cylinders. The authors considered the flow regime to be turbulent and a pipe with a contraction ratio of two and another without contraction subjected to a constant heat flux as the boundary condition. The results of the numerical simulations reported by the authors revealed that the maximum increase in the heat transfer coefficient corresponds to the annular pipe with a contraction ratio of two due to the recirculation zone generated which started before the point of separation of the flow at the wall (ABDULRAZZAQ *et al.*, 2020a) investigated numerically and experimentally the turbulent flow of the nanofluids $\text{Al}_2\text{O}_3\text{/Water}$ and $\text{TiO}_2\text{/Water}$ in an annular pipe with sudden contraction and another without a change in geometry. The authors reported that the maximum increase in thermal performance was 194.6 % in the annular channel with a contraction ratio of two

compared to the straight pipe. The authors attributed the increase in heat transfer to the recirculation zone and the flow separation region downstream of it. It was also reported that among the nanofluids investigated, $\text{Al}_2\text{O}_3/\text{Water}$ with a volumetric concentration of 2 % showed the best thermal performance.

(TOGUN et al., 2023b, 2023a) Investigated numerically the thermal enhancement of nanofluid flow in FFS reduction channels with and without ribs as obstacles. The authors concluded that the use of ribs causes an increase in heat transfer and pressure drop. They noted also that the pressure coefficient decreases after each rib, but increases behind it, leading to a flow reversal. (AZODINIA et al., 2023) numerically investigated nanofluid flow of $\text{Al}_2\text{O}_3/\text{Water}$ in a microchannel with a circle bump in the corner of the microchannel, according to the presented simulations the presence of circle bump led to an improvement in heat transfer by 11.60 %.

Similarly to the work on nanofluid flow under expansion, works on heat transfer in nanofluid flow considering contraction effects are quite limited, with the vast majority of work on the subject being carried out numerically. The key results of the main studies on the subject are shown in Table 2.5, where researchers have focused mainly on analyzing the Nusselt number and the heat transfer coefficient in flows under contraction for different nanofluids.

Table 2.5 – Summary of the state-of-the-art involving heat transfer in nanofluid flow under contraction.

Author	Nanofluid	Nanoparticle concentration %	Contraction ratio	Findings
(SAFAEI <i>et al.</i> , 2014)*	FMWCNT/Water	0.1 - 0.25 wt. %	2	For FMWCT h ↑ 12.17 % Nu ↑ 10.85 %
(KHERBEET <i>et al.</i> , 2014)**	Al ₂ O ₃ /Water SiO ₂ / Water	0 - 1 vol. %	1.5 (microchannels)	For Al ₂ O ₃ : h ↑ 22.1 % For SiO ₂ : h ↑ 30.6 %
(TOGUN <i>et al.</i> , 2015)*	Al ₂ O ₃ /Water CuO / Water	1 - 4 vol. %	Case 1 (Double FFS): 10:8:6 (in cm) Case 2 (Double FFS): 10:6:4 (in cm) Case 3 (Double FFS): 10:4:2 (in cm)	For Al ₂ O ₃ : Nu ↑ 10.09 % For CuO: Nu ↑ 7.88 %
(BESANJIDEH <i>et al.</i> , 2016)*	Al ₂ O ₃ / Water	5 vol. %	1.25; 2; 3.33	For Al ₂ O ₃ and CR = 1.25: Nu ↑ 27 % For Al ₂ O ₃ and CR = 2: Nu ↑ 20 % For Al ₂ O ₃ and CR = 3.33: Nu ↑ 11 %
(HASHIM <i>et al.</i> , 2017)*	Al ₂ O ₃ / Water CuO / Water ZnO / Water SiO ₂ / Water	0 - 4 vol. %	1.33; 2; 4	For Al ₂ O ₃ : Nu ↑ 4.19 % For CuO: Nu ↑ 1.43 % For ZnO: Nu ↑ 5.74 % For SiO ₂ : Nu ↑ 12.32 %

Source: Author's own.

* Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

Table 2.5 – (continued).

Author	Nanofluid	Nanoparticle concentration %	Contraction ratio	Findings
(ALRASHED <i>et al.</i> , 2018)*	FMWCNT / Water	0 - 0.25 wt. %	2	For FMWCT Nu ↑ 5.66 % For FMWCT Nu ↑ 11.78 %
(ABDULRAZZAQ <i>et al.</i> , 2020c)*	TiO ₂ / Deionized water	0.5 - 2 vol. %	2	For TiO ₂ : h ↑ 248.02 %
(ABDULRAZZAQ <i>et al.</i> , 2020b)**	Al ₂ O ₃ / Deionized water TiO ₂ / Deionized water	0.5 - 2 vol. %	1.25; 1.67 e 2	For Al ₂ O ₃ : h ↑ 221.5 % For TiO ₂ : h ↑ 200.2 %
(TOGUN <i>et al.</i> , 2021)*	Al ₂ O ₃ - Cu / Water	0.1 - 2 vol. %	Case 1 (Double FFS): 5:1:1 (in cm) Case 2 (Double FFS): 5:2:1 (in cm) Case 3 (Double FFS): 5:1:2 (in cm)	For Al ₂ O ₃ : h ↑ 2 %
(AZODINIA <i>et al.</i> , 2023)	Al ₂ O ₃ / Water	2 vol. %	2	For Al ₂ O ₃ : Nu ↑ 84.28 %
(TOGUN <i>et al.</i> , 2023a)*	Al ₂ O ₃ / Water CuO / Water	1 - 4 vol. %	2	For Al ₂ O ₃ and CuO with Re = 40000; h ↑ 70 %
(TOGUN <i>et al.</i> , 2023c)*	Al ₂ O ₃ / Water	1 - 4 vol. %	2 (contraction with ribs)	For Al ₂ O ₃ : Nu ↑ 26.22 %

Source: Author's own.

*Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

2.3.4 Proposed correlations

Correlations proposed for the average Nusselt number in nanofluid flows with a sudden geometry change are very scarce in the literature, even for conventional fluids in a single-phase flow, there is a lack of work on the subject, even when it comes to correlations for pressure drop. Table 2.6 shows the correlations proposed for the average Nusselt number and performance efficiency index (PEI) based on numerical and experimental investigations, which are specific to the geometries used by each author. In general, none of the existing correlations appear to be completely satisfactory for general use in pipes with a change in geometry (MONTAZER *et al.*, 2020b).

Table 2.7 shows some correlations for pressure drop in flows with a sudden geometry change, with and without nanofluids. Similar to the correlations for heat transfer, the attributes for pressure drop in nanofluids are characterized by variations in the thermophysical properties of the nanofluids (AMBREEN and KIM, 2018). As can be seen in Table 2.7, the proposed correlations are based on curve fitting of the experimental or numerical data used, so there are no correlations in the literature with total accuracy to predict the pressure drop satisfactorily for any nanofluid flowing under contraction or expansion.

Table 2.6 – Correlations for heat transfer of nanofluids in sudden geometry change.

Author	Correlation	Nanofluid	Comments
(KIMOUCHE <i>et al.</i> , 2017)*	$\overline{Nu} = (0.494 * Re^{0.763}) * \left(0.854 + \left(0.362 + 0.375 * \left(\frac{\rho_s}{\rho_f} \right)^{0.0738} \right) * \phi^{0.909} \right)$ $\overline{Nu} = (0.494 * Re^{0.763}) * \left(0.854 + \left(0.622 + 0.119 * \left(\frac{\kappa_s}{\kappa_f} \right)^{0.0754} \right) * \phi^{0.909} \right)$	Ag / Water Cu / Water CuO / Water Al ₂ O ₃ / Water	$Re > 5000$; $\phi \leq 0.2$; Expansion ratio of 1.53
(NOURI <i>et al.</i> , 2018)*	$\overline{Nu} = 0.5 * Re^{0.63} * Pr^{0.25} * \lambda^{-0.032}$	CuO / Water	$60 \leq Re \leq 1000$; $1 \leq \phi \leq 6$; $0.2 \leq \lambda \leq 0.6$; Expansion ratio of 2
(MONTAZER <i>et al.</i> , 2020b)***	$Nu_{\left(\frac{X}{H}\right)} = \begin{cases} 61.77 - 78.98 * \phi + 0.0063 * Re - 13.79 * Pr + 26.44 * \left(\frac{X}{H}\right) \\ - 1.47 * \left(\frac{X}{H}\right)^2 + 0.025 * \left(\frac{X}{H}\right)^3 ; & 0 \leq \left(\frac{X}{H}\right) \leq \left(\frac{X}{H}\right)_{peak} \\ 348.68 - 40.63 * \phi + 0.0069 * Re - 8.41 * Pr - 13.43 * \left(\frac{X}{H}\right) \\ 0.204 * \left(\frac{X}{H}\right)^2 - 0.001 * \left(\frac{X}{H}\right)^3 ; & \frac{X}{H} > \left(\frac{X}{H}\right)_{peak} \end{cases}$ $\overline{Nu} = 1.16 * Re^{0.55} * Pr^{-0.312} * (1 + \phi)^{-0.25}$	GNP / DW MWCNT / DW SiO ₂ / DW ZnO / DW	$4000 \leq Re \leq 16000$; $0.025 \leq \phi \leq 0.2$; $0.2 \leq \lambda \leq 0.6$; Expansion ratio of 2 ; $Nu_{\left(\frac{X}{H}\right)}$ (Nu local)

Source: Author's own.

*Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

Table 2.6 – (Continued).

Author	Correlation	Nanofluid	Comments
(KLAZLY and BOGNAR, 2022)*	$PEI(TiO_2) = 120.7 \cdot \phi^3 - 116.31 \cdot \phi^2 + 1.6322 \cdot \phi + 1.00017$	TiO ₂ /Water	$Re = 280;$ $0.01 \leq \phi \leq 0.04;$
	$PEI(Al_2O_3) = 1324.7 \cdot \phi^3 - 119.76 \cdot \phi^2 + 1.2082 \cdot \phi + 1.0018$	Al ₂ O ₃ /Water	Expansion ratio of 1.67
(AZODINIA et al., 2023)*	$\overline{Nu} = (-17.53313) + (18.63447 - (-17.53313)) \cdot \frac{0.49339}{(1+1.13333 \cdot 10^{(9.67977-x)})} +$ $(18.63447 - (-17.53313)) \cdot \frac{(1-0.49339)}{1-1.0773 \cdot 10^{(9.71143-x)}}, (1)$	Al ₂ O ₃ / Water	$Re = 25;$ $\phi = 2 \%; (1)$
	$\overline{Nu} = 1.89761 + 1.26972 \cdot \left(e^{(-(x-9.99877) \cdot \frac{(x-9.99877)}{(2 \cdot 0.29345)})} + (1 - 0.5 \cdot (1 - \tanh(2.1538 \cdot (x - 11.82359)))) \cdot (-0.44825) \cdot e^{(-0.5 \cdot (-14.11236) \cdot (ABS(x-13.78396) + (x-13.78396)))} \right), (2)$		$Re = 100;$ $\phi = 2 \%; (2)$ CR = 2

Source: Author's own.

*Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

Table 2.7 – Head loss correlations for heat transfer of nanofluids/work fluid in sudden geometry change.

Author	Correlation	Nanofluid/work fluid	Comments
(BULLEN <i>et al.</i> , 1987)***	$K_c = \frac{2 * g * \overline{A_2^2} * h_A}{Q^2} - \left[1 - \left(\frac{A_{2c}}{A_{1c}} \right)^2 \right]$	Water	$4 \cdot 10^4 \leq Re \leq 2 \cdot 10^5$; Contraction ratios (CR) of 0.13 to 0.7; $K_c \uparrow 25\%$ for CR = 0.135
(BALAKHRISNA <i>et al.</i> , 2010)**	$\beta = \frac{Q_w}{Q_w + Q_o}$ $\frac{\Delta P}{\rho_m} \pm \frac{(\sigma^4 - 1) * U_m^2}{2} = h_f$ $\rho_m = \beta * \rho_w + (1 - \beta) * \rho_o$ $h_f = k_1 * \frac{U_m^2}{2} \text{ for a contraction}$ $h_f = k_2 * \frac{U_m^2}{2} \text{ for an expansion}$	Oil - Water	The experimental values of contraction and expansion coefficients are found to be lower for oil- water as compared to only water flow through the same test rigs
(ZHANG <i>et al.</i> , 2019)*	$K = \frac{2 * T_m * \dot{S}_{tot}}{\dot{m} * u_m^2}$	Cu / Water	$8 \leq Re \leq 256$; $\phi \leq 6$; Expansion ratio of 2 ; If $Re \uparrow$ $K \downarrow$ and $\dot{S}_{tot} \uparrow$

Source: Author's own.

*Numerical investigation; ** Numerical and experimental investigation; *** Experimental investigation

2.4 Conclusions

The focus of this review is on computational and experimental investigations of heat transfer enhancement in the flow of nanofluids through conduits with sudden expansion and/or contraction, as well as in backward-facing step (BFS) and forward-facing step (FFS) channels for thermal system applications. The following conclusions were drawn:

- **Heat Transfer Enhancement:** One of the primary observations is that the heat transfer rate significantly increases with the expansion area in annular pipes and with the step height in BFS and FFS channels. Additionally, as the Reynolds number increases, so does the heat transfer rate. These findings indicate that manipulating these parameters can effectively enhance the thermal performance of nanofluids in various configurations.
- **Effect of Contraction and Expansion:** Although flows with contraction also show an increase in the convective heat transfer coefficient, this effect is generally smaller compared to flows with sudden expansion. The recirculation zone that forms immediately after a sudden geometric change in the flow is a crucial factor. This zone facilitates the conversion of turbulent kinetic energy into heat transfer through viscous effects. However, the turbulent structures formed upstream of the flow lead to flow separation, which increases the pumping power required to reach a reattachment point. This process is essential to avoid pressure loss and bubble formation within the pipe, which could potentially lead to cavitation.
- **Impact of BFS and FFS Channels in Nanofluid Flow:** In BFS channels with sudden contraction, literature indicates that a reduction in flow velocity decreases the coefficient of friction, pressure drop, and heat transfer coefficient in various channel sections. At high Reynolds numbers, adding solid nanoparticles to the base fluid significantly enhances heat transfer. However, this enhancement comes with trade-offs, as the presence of nanoparticles also affects the friction factor, pressure drop, and pumping power. In FFS channels, the Nusselt number increases with the volume concentration of the nanofluid but decreases as the diameter of the nanoparticles increases. Furthermore, the flow velocity tends to increase as the density of the nanofluid decreases.
- **Discrepancies in Results** Despite the relative consistency observed between numerical and experimental results in some studies, there are notable discrepancies between the

results obtained by different researchers using the same nanoparticles and test conditions. Most studies have been conducted numerically, highlighting a need for more experimental results, particularly for turbulent and transitional flows, to draw more objective conclusions relative to numerical data.

- **Limitations of Existing Correlations:** Despite proposed correlations in the literature for the Nusselt number and pressure drop in nanofluid flows with sudden geometry changes, none are fully satisfactory for general use. These correlations apply only to specific cases, contingent on problem boundary conditions and the nanoparticles used. This limitation highlights the necessity for more comprehensive models that can be universally applied across different geometries and conditions.

While significant advancements have been made in understanding the behavior of nanofluid flows in complex geometries, there remains a considerable need for further experimental research. Such research is essential to bridge the gaps between numerical predictions and real-world behavior, ultimately leading to more reliable and universally applicable correlations for heat transfer and fluid flow in nanofluid systems.

CHAPTER III

EXPERIMENTAL PROCEDURES

This chapter explores the experimental procedures critical to evaluate the thermohydraulic performance of nanofluid flow in closed conduits with geometry change. All nanofluids performed were based on a mixture of water and ethylene glycol with a ratio of 50:50 % in weight (H_2O – EG 50:50 % wt.). For this purpose, several preliminary steps were undertaken and are presented in this chapter. The first step describes the method used to produce nanofluids as well as the analysis of their stability. The second step involves the measurement of the thermophysical properties of the produced nanofluids, such as thermal conductivity, dynamic viscosity, and density. The third step consists of detailing the modifications made to the experimental setup, their validation, and the analysis of uncertainties in the measured and calculated variables.

3.1 Synthesis of nanofluids

The two-step method was employed to produce the nanofluid samples investigated in this work. According to Ali and Salam (ALI and SALAM, 2020b), this method is commonly used in the commercial-scale production of nanofluids due to its simplicity of preparation. It is also the preferred method of most researchers. Through this approach, nanoparticles are produced separately and subsequently dispersed in a base fluid, in which they are synthesized by magnetic stirring, ultrasonication, or high-pressure homogenization (CÁRDENAS GÓMEZ et al., 2017).

As mentioned before, two different nanoparticles were dispersed on a mixture of H_2O - EG 50:50 % in weight. The first was the multi-walled carbon nanotube (MWCNT), provided by

Nanostructures & Amorphous Material Inc. The second one was the multilayer graphene films were obtained through the exfoliation of 6 mg of graphite, provided by *Laboratório de Filmes Finos e Processos de Plasma* at *Instituto de Ciência Tecnologia e exatas* (ICTE) of *Universidade Federal do Triângulo Mineiro* (UFTM), dispersed in 30 ml of isopropyl alcohol. The dispersion was then divided into three equal parts, with each part subjected to ultrasonic treatment for 30, 60, and 90 minutes, following the methodology outlined by (MACHUNO *et al.*, 2015). Another graphene sample were a commercially available graphene variant comprising nanoplates and functionalized with its production process described by (RASHIDI *et al.*, 2023).

The nanoparticles were dispersed on a mixture of water and ethylene glycol with a mass concentration of 50 % of each fluid (H₂O - EG 50:50 % wt.). The geometric characteristics and thermophysical properties of the nanoparticles and base fluid used in the current study are presented in Table 3.1. A routine described in Fig. (3.1), based on the two-step method, was established to produce the nanofluid samples, which also used an ultrasonic disrupter as the dispersal mechanism.

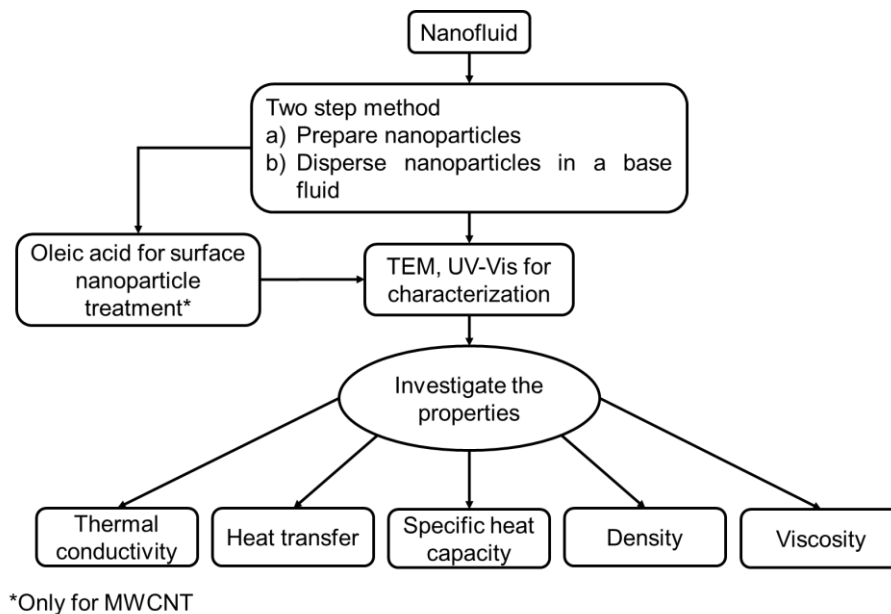


Figure 3.1 – Nanofluid production process. Source: Author's own.

For the dispersion of MWCNT and graphene nanofluids, it was necessary to apply an external energy. The mixture was sonicated for 40 minutes with a power of 300 W at room temperature using an ultrasonic processor Q500 with an adjustable pulse on and off for 5

seconds. Following ultrasonication, the chains of oleic acid molecules surrounding the MWCNTs are stretched, creating a physical barrier between the chains due to the same charge. This barrier prevents van der Waals forces between them, thereby enhancing dispersion and improving the thermal performance of the nanofluid. Fig. (3.2) shows the nanofluid synthesis process.

Table 3.1 – Thermophysical properties of nanoparticles and base fluids.

Parameters	Water	Ethylene glycol	MWCNT	Graphene
Density (kg/ m ³)	997.1	1113.2	2100	2200
Thermal conductivity (W/ m K)	0.607	0.258	3000	1000-5000
Specific heat (kJ/ kg K)	4.180	2.347	0.710	0.710
Purity	-	-	95 %	95 %
Average size (nm)	-	-	20 – 30	50 - 2000
Length (µm)	-	-	10 - 50	-
Thickness (nm)	-	-	-	3 - 6

*The base fluid data aligns with (STANDARD, 1978), while the nanoparticle data was supplied by the manufacturer, except for industrial graphene, which remains industrial property information. Source: Author's own.

Also, oleic acid was applied to evaluate the stability of the MWCNT scattering in the base fluid. Ultracentrifugation was performed for 4 hours at 8000 RPM in a UNIVERSAL 320R centrifuge to separate the solid and liquid phases of MWCNT and oleic acid, in this way, oleic acid acts as a functionalizing agent, improving the dispersion of the nanoparticles in the base fluid. This sample was called FMWCNT (functionalized MWCNT). The functionalization process for MWCNT is described in Fig. (3.3).

Table 3.2 details the main features of the samples, including base fluid and mass fraction. Using EES (Engineering Equation Solver) software, the mass of nanoparticles in the base fluid was calculated. The mass concentrations for each carbon nanotube sample were 0.005 % wt., 0.01 % wt., and 0.05 % wt., with a final volume of 3500 ml. For graphene, two concentrations were investigated: 0.005 % wt. and 0.01 % wt. at the same volume. Industrial graphene was also tested at 0.005 % wt. and 0.01 % wt. It's important to highlight that for industrial graphene

samples the graphene powders were functionalized with long-chain organic molecules with polar ends before being added to the base grease.

Table 3.2 – Description of nanofluid samples used in the present work.

Sample	Base fluid	Mass fraction (% wt.)	Surface modification
MWCNT	H ₂ O-EG 50:50 % wt.	0.005; 0.01; 0.05	No
Graphene		0.005 and 0.01	No
Industrial graphene		0.005 and 0.01	No
FMWCNT		0.005; 0.01; 0.05	Oleic Acid

Source: Author's own.

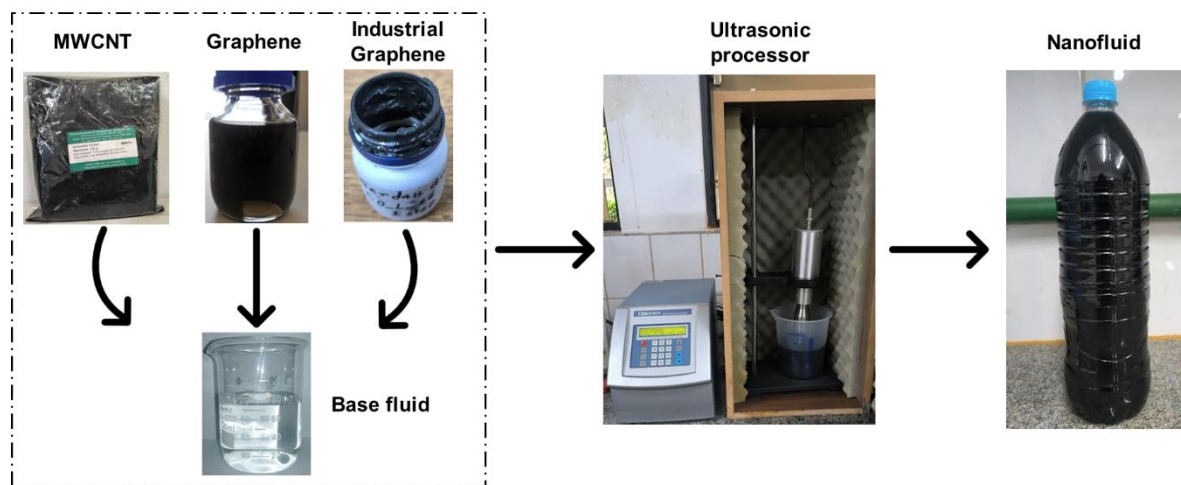


Figure 3.2 – Nanofluid synthesis process. Source: Author's own.

The results from the nanofluids synthesis and characterization performed in this work are shown in Fig. (3.4), Fig. (3.5) and Fig. (3.6). Fig. (3.4) shows the Nanofluid samples after preparation, and Fig. (3.5a) – Fig. (3.5d) depict TEM images of MWCT, FMWCNT, graphene and industrial Graphene using a transmission electron microscope Hitachi (HT7700). For morphological nanoparticles visualization the samples were prepared by dispersing them in an ultrasonic bath within an alcoholic medium. A drop of the sample was then placed on the surface of a copper grid and allowed to dry under controlled flow conditions prior to imaging. The

software ImageJ was used to process the images and obtain the nanoparticles diameter. Fig (3.6a) – Fig (3.6d) depict SEM images of MWCT, FMWCNT, graphene and industrial graphene using scanning electron microscope Zeiss (EVO MA10). The SEM images were complemented by energy dispersive x-ray detector (EDX) analysis to analyze this spectrum and determine the chemical composition of the nanoparticles investigated (See **APPENDIX A**).

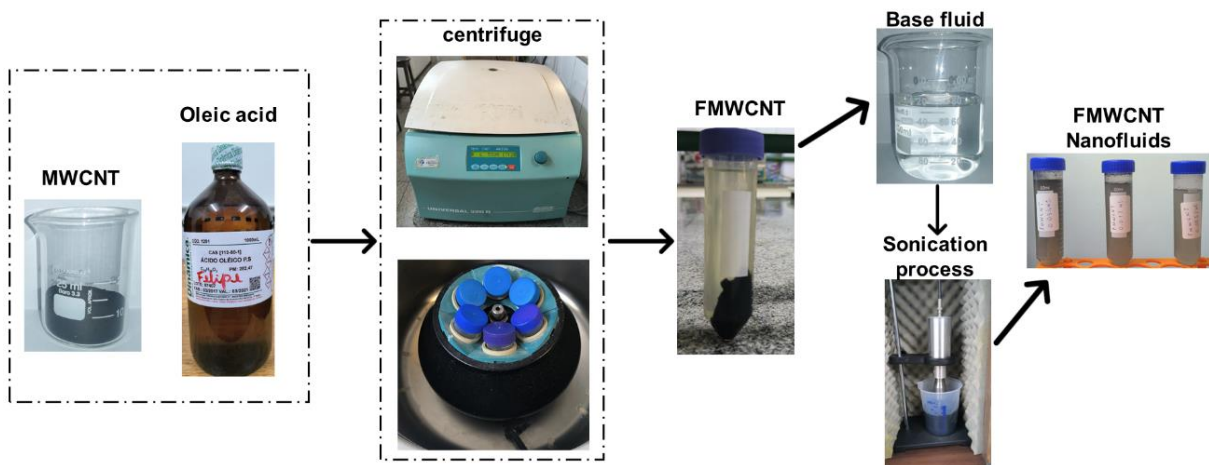


Figure 3.3 – Functionalization process for MWCNT. Source: Author's own.

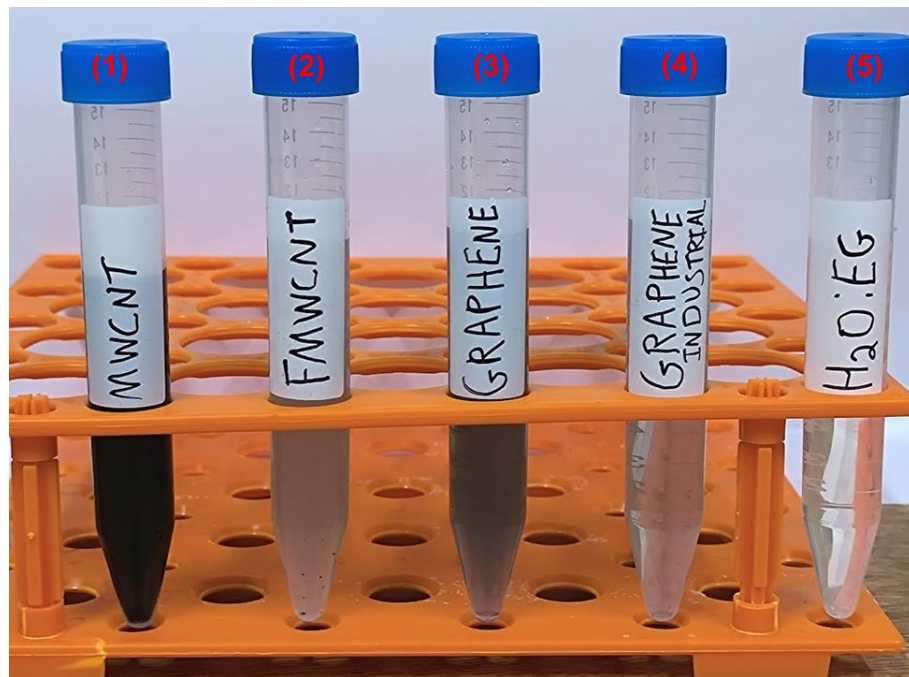


Figure 3.4 – Nanofluids samples (1 - MWCNT; 2 - FMWCNT; 3 - Graphene and 4 - Industrial Graphene) in the highest mass concentration and base fluid (5 - H₂O: EG 50:50 % wt.). Source: Author's own.

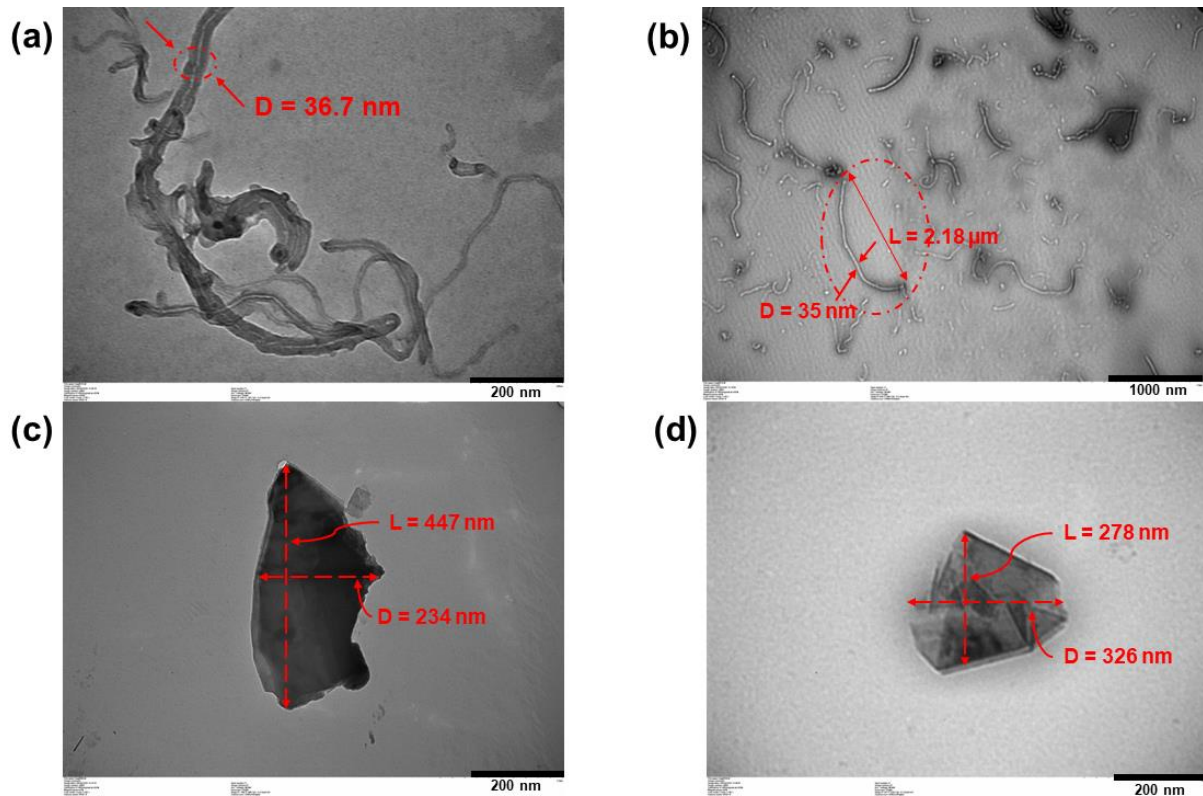


Figure 3.5 – TEM images for (a) MWCNT; (b) FMWCNT; (c) Graphene and (d) Industrial graphene. Source: Author's own.

The morphological characteristics of MWCNT, FMWCNT, graphene, and industrial graphene were analyzed using TEM and SEM techniques. TEM images reveal that MWCNTs have a consistent diameter of 36.7 nm, displaying long, entangled tubes typical of multi-walled carbon nanotubes, while FMWCNTs, with a diameter of 35 nm and a length of 2.18 μm , exhibit a rougher texture due to functional groups attached to their surfaces. Graphene samples show few-layer structures with lateral dimensions of 447 nm in length and 234 nm in diameter, indicating effective exfoliation, whereas industrial graphene presents larger, thicker flakes with dimensions of 278 nm in length and 326 nm in diameter, suggesting less efficient exfoliation or more stacked layers.

SEM images complement these observations by revealing the surface morphology of the samples. MWCNTs form a dense, web-like network of intertwined tubes, providing a high surface area. In contrast, FMWCNTs exhibit a more granular appearance due to increased surface roughness from functionalization. Graphene appears as overlapping flakes with clear edges and few-layer thickness, displaying its planar nature with occasional crumpling or folding. Industrial graphene, however, shows larger, irregularly shaped flakes with pronounced

thickness. These morphological differences, influenced by preparation and functionalization processes, have significant implications for the physical and chemical properties of the nanomaterials, impacting their potential applications.

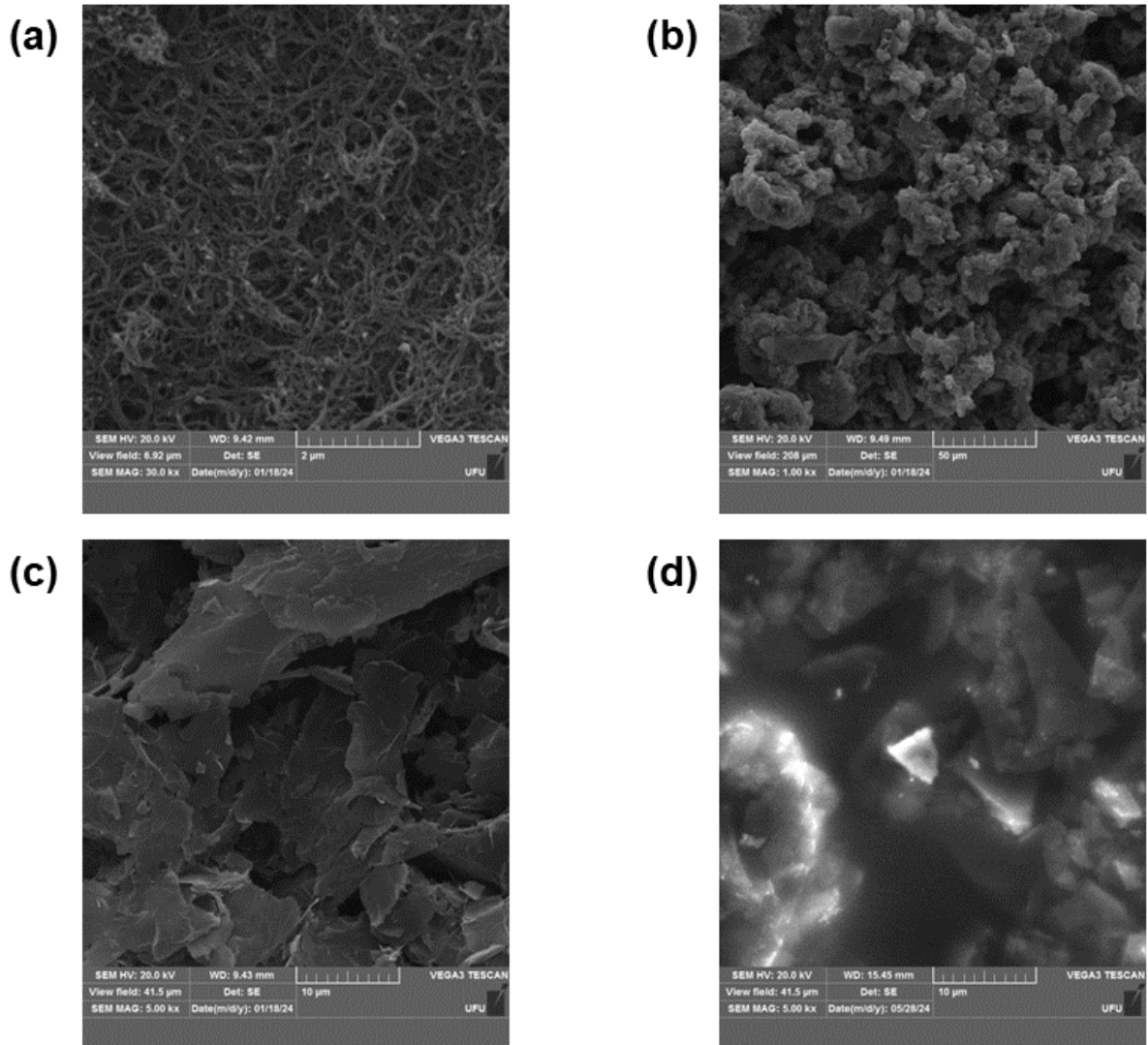


Figure 3.6 – SEM images for (a) MWCNT; (b) FMWCNT; (c) Graphene and (d) Industrial graphene. Source: Author's own.

3.2 Stability analysis

Nanofluid stability was evaluated by obtaining optical absorption spectra through UV-VIS spectroscopy (UV-VIS; Shimadzu; UV-1900), as shown in Fig. (3.7). The procedure described in (JIANG et al, 2003) was used to analyze the nanofluid stability by measuring the

absorbance at different periods. This methodology allows for the quantitative evaluation of sample sedimentation over time, given the initial relationship between absorbance and nanoparticle volumetric concentration. This relationship is described by the Beer-Lambert law (SWINEHART, 1962), as represented in Eq. (3.1), where C_0 and C are the values of the initial concentration and the relative concentration after a specific time. In this equation, A_0 and A are the absorbance values measured using UV-VIS spectroscopy. The wavelength peaks ranging from 190-1100 nm were used to obtain the absorbance and mass concentration relationship.

$$\eta = \frac{C_0 - C}{C_0} \cdot 100\% = \frac{A_0 - A}{A_0} \cdot 100\% \quad (3.1)$$

and,

$$A = \log \frac{I_0}{I} = \varepsilon \cdot c \cdot d \quad (3.2)$$

where I_0 and I represent the intensity of the measurement beam before and after it passes through the sample, respectively. The molar absorption coefficient is denoted as ε , c indicates the concentration of nanoparticles, and d is the path length of the measurement beam through the sample.

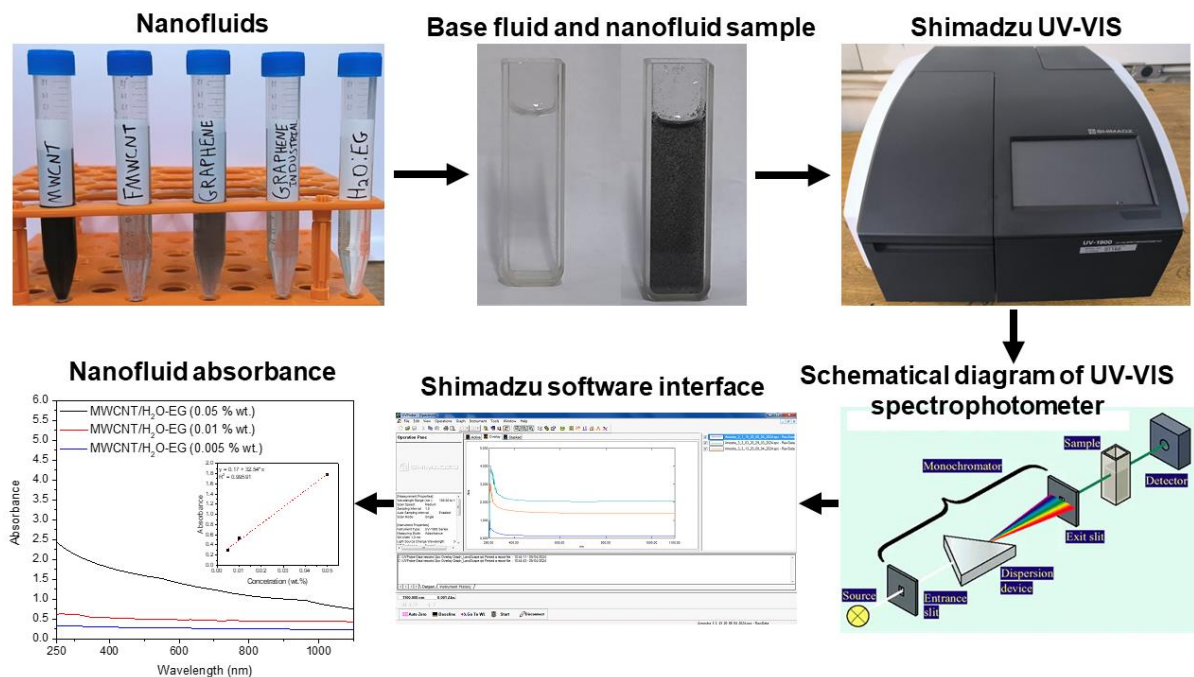


Figure 3.7 – UV – VIS spectrophotometer routine. Source: Author's own.

The UV-VIS spectrum, characterized by broad absorption bands resembling Gaussian functions, corresponds to the wavelength required for electronic transitions based on nanoparticle optical properties. Nanofluid samples were analyzed for optical absorption between 190 nm and 1100 nm using a 10 mm quartz cuvette. The initial absorbance-concentration relationship was determined from the linear fit at the spectrum's maximum absorption point, following the Beer-Lambert law. Colloidal stability was assessed over seven days to measure sedimentation, and UV-VIS spectroscopy also evaluated nanofluid stability post-experimental tests.

3.3 Thermophysical properties

After completing the preparation and stability evaluation procedures, the thermophysical properties of the nanofluid samples, e.g., thermal conductivity, dynamic viscosity, and density were measured. Experimental values for these properties were obtained using a thermal conductivity meter and a viscometer at the *Laboratório de energia, Sistemas térmicos, and Nanotecnologia* (LESTnano) in the *Universidade Federal de Uberlândia* (UFU). These methods and results are detailed in the following subsections.

3.3.1 Thermal conductivity

In the present work, the thermal conductivity values of nanofluid samples were obtained using a LINSEIS conductivity meter, model THB-1, Fig. (3.8), which employs the hot transient bridge technique. It is an improved hot wire technique to gauge properties (thermal diffusivity, specific heat, and thermal conductivity) accurately. This technique enables the measurement of thermal conductivity, thermal diffusivity, and specific heat of a wide range of materials, including solids, liquids, powders, and pastes.

The measurement is automatic and performed by the software provided by the manufacturer, with ten measurements per cycle and 2 to 3 cycles per sample. The measurement probe generates a constant heat flux over a specified period, recording temperature changes in the surrounding sample. For a homogeneous and isotropic medium, thermal conductivity is calculated using the temperature-time relationship and the probe's geometric characteristics, as described by Eq. (3.3):

$$\kappa_m = \frac{P_0 \cdot L}{\Delta T(t) \cdot F(t)} \quad (3.3)$$

where P_0 is the constant heat flux per unit time and area, L is the length of each resistor, t is the elapsed time the initiation of current, ΔT is the average temperature change, $F(t)$ is geometry – dependent property of the sensor, and κ_m is the thermal conductivity of the material being measured.



Figure 3.8 – Thermal conductivity meter LINSEIS and THB – 1 sensor. Source: Author's own.

During the thermal conductivity measurement process, the sensor is placed into a reservoir cavity holding approximately 20 ml of the sample. The stainless-steel reservoir features a double-wall design that allows for heat exchange with the fluid from the thermal bath, achieving the target reference temperature. The thermal bath used for this procedure is the MQBMP-01 model, manufactured by MicroQuimica Ltda. Fig. (3.9) shows the configuration of the experimental setup, where the thermal conductivity was measured over a temperature range from 30 °C to 50 °C. For each temperature value, 10 measurements were taken, with the final value being the arithmetic mean of the results obtained. It is important to highlight that the measurements were conducted with high precision, and the conclusions are applicable to the evaluated temperature range.

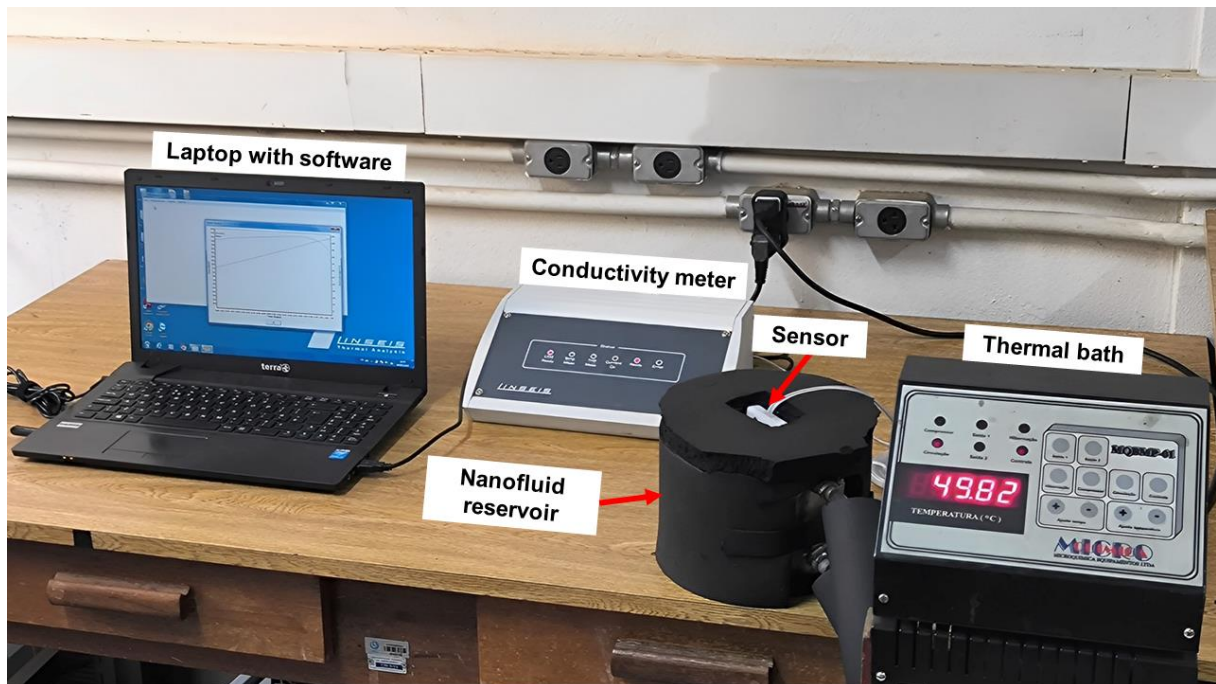


Figure 3.9 – Experimental setup for thermal conductivity measurement. Source: Author's own.

The THB-1 thermal conductivity meter is interfaced directly with a computer equipped with dedicated software for parameter control and result visualization. Measurement is performed automatically once the specified test conditions are achieved. The uncertainty ranges associated with the measurements, as specified by the manufacturer, are detailed in Table 3.3.

Table 3.3 – Specifications of THB – 1 LINSEIS provided by manufacturer.

Parameter	Temperature range	Measurement range	Measurement uncertainty
Thermal conductivity	30 °C to 50 °C	0.01 to 1 W/(mK)	Better than 2 %
Thermal diffusivity		0.05 to 10 mm ² /s	Better than 5 %
Specific heat		100 to 5000 kJ/(m ³ K)	Better than 5 %

Source: Author's own.

3.3.2 Density and dynamic viscosity

The dynamic viscosity and the nanofluid samples' density were measured using a rotational viscometer, model StabingerTM SVMTM 3000, from Anton Paar (Fig. 3.10), which has a cylindrical geometry with concentric tubes. The temperature was controlled in the range of

20 °C to 80 °C. Simultaneously, the equipment measures dynamic viscosity, kinematic viscosity, and density. The measurement principle of this apparatus is an enhanced version of the Couette system, utilizing high-resolution torque and rotational speed measurements. It features a Peltier element that accommodates a broad range of viscosities (from 0.2 mPa·s to 20,000 mPa·s) and temperatures (from -56 °C to 105 °C) within a single unit. The device requires only a minimal sample volume of approximately 2.5 ml and is equipped with a specific mass measurement cell based on the U-tube oscillation principle. Both the viscosity and density cells are filled concurrently during the same process, thus streamlining the measurement procedure, and enabling simultaneous data acquisition.



Figure 3.10 – Viscometer StabingerTM SVMTM 3000, from Anton Paar. Source: (CONTRERAS et al., 2019).

The viscometer StabingerTM SVMTM 3000 employs a rotating magnet system to generate an induced current field, creating a braking moment proportional to the rotor's speed. The measurement process begins automatically when the measurement cell, containing the sample, reaches a constant rotor speed. The rotor's bearing-free, floating design ensures immunity to vibrations. Dynamic viscosity is measured by balancing the induced current's braking effect with the sample's shear forces, ensuring precision. Table 3.4 details the uncertainty measurements for viscosity, density, and temperature, as well as their repeatability, confirming the instrument's reliability.

Table 3.4 – Uncertainty data of Anton Paar viscometer measurement provided by the manufacturer.

Parameter	Temperature range	Measurement range	Measurement uncertainty
Dynamic viscosity	20 °C to 80 °C	± 0.35%	± 0.1% of measured value
Density		± 0.0005%	± 0.0002 g/cm ³
Temperature		± 0.02%	± 0.0005 °C

Source: Author's own.

3.3.3 Specific heat

The specific heat capacity of coolants was determined by the mixture model in which the thermal equilibrium between the mixture of H₂O - EG 50:50% wt. and the nanoparticles are considered, according to (XUAN and ROETZEL, 2000):

$$C_{p_{nf}} = \frac{(1-\phi) \cdot (\rho \cdot C_p)_{bf} + \phi \cdot (\rho \cdot C_p)_{np}}{(1-\phi) \cdot \rho_{bf} + \phi \cdot \rho_{np}} \quad (3.4)$$

where C_p denotes the specific heat capacity, ϕ is the nanoparticle volume fraction in the base fluid, and ρ is the density. The subscripts np , nf , and bf denote the nanoparticle, nanofluid, and base fluid, respectively. The specific heat of base fluid ($C_{p_{bf}}$) was taken experimentally. The specific heat of nanoparticle ($C_{p_{np}}$) and the nanoparticle density (ρ_{np}) were provided by the manufacturer.

3.4 Experimental setup

An experimental setup, Fig (3.11), featuring a closed-loop setup was employed to assess forced convective heat transfer of single-phase flow across laminar and turbulent regimes, particularly focusing on sudden expansion and contraction. The test section comprised a smooth-walled circular copper tube measuring 1700 mm in length, with an inside diameter of 14.29 mm and an outside diameter of 15.87 mm. This setup facilitated the evaluation of heat transfer and pressure drop of nanofluid flow under uniform heat flux conditions.

The experimental apparatus consists of multiple integrated systems, including a main circulation system, a temperature control system, and a cooling system. The main circulation system is responsible for maintaining the desired flow rate of the nanofluid through the test section. This system is equipped with a gear pump, a Coriolis flow meter, and a preheating circuit to stabilize the fluid's temperature before it enters the test section. The temperature control system ensures that the inlet temperature of the test section remains constant, thus providing a stable thermal boundary condition for the experiments.

Heat is supplied to the test section using flexible polyimide electrical resistances, which are uniformly distributed along the length of a smooth-walled copper tube. For the expansion case, flexible heating tapes OMEGALUXTM was employed. This tube is insulated to minimize heat loss and is fitted with precise instrumentation to measure temperature and pressure at various points. The temperature measurements are obtained using PT100 three-wire RTD temperature transmitters, while the pressure drop across the test section is recorded using piezoresistive pressure transmitters.

Data acquisition and monitoring use a LabView[®]-based system for real-time data collection and analysis. This system captures a wide range of variables, ensuring comprehensive and accurate experimental data. The setup is validated through uncertainty analysis, quantifying measurement accuracy based on instrument uncertainties. This rigorous approach ensures reliable results for evaluating the thermohydraulic performance of the nanofluids.

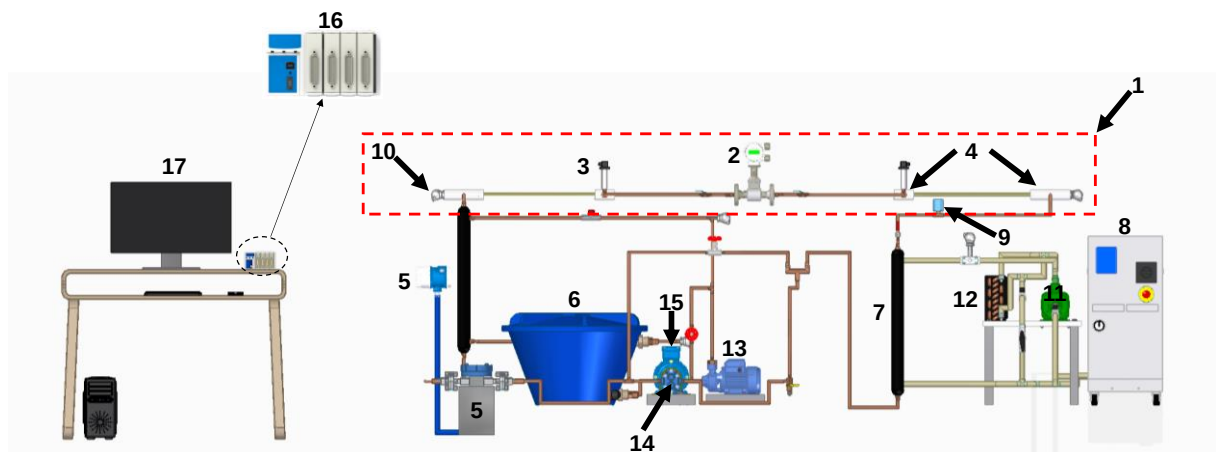


Figure 3.11 – Test bench for measuring nanofluid flow and heat transfer. 1: Test section; 2: Differential pressure transmitter; 3: Pressure transmitter; 4: Nylon supports; 5: flow meter; 6: Preheating system; 7: Heat exchanger; 8: Water chiller; 9: Nanofluid reservoir; 10: Temperature transmitter; 11: Water pump; 12: Condensing unit; 13: Water pump; 14: Gear pump; 15: Electric motor; 16: Data Acquisition (NI-DAQ); 17: Computer. Source: Author's own.

3.4.1 Test section

The test section, which consists of a 1700 mm long smooth-walled circular copper tube with an inside diameter of 14.29 mm and an outside diameter of 15.87 mm (a 5/8" commercial copper tube), was prepared to provide data that allow the calculation of pressure drop and heat transfer coefficient by convection of the nanofluid in laminar and turbulent regime, with uniform heat flux. In cases involving contraction, nanofluid flowed from a 7/8" into the test section with a 5/8" pipe (CR = 1.4). In another scenario, nanofluid transitioned from 9/8" to 5/8" pipe (CR = 1.9). For expansion case, before entering in the test section, the nanofluid flow from a 3/8" heated pipe to the test section, a 5/8" pipe, (ER = 1.7). It's noteworthy that all test sections featured an entrance region of 40 cm to ensure the fully developed flow. Fig (3.12) depicts the cross – section for contraction and expansion cases and a real image of this sections.

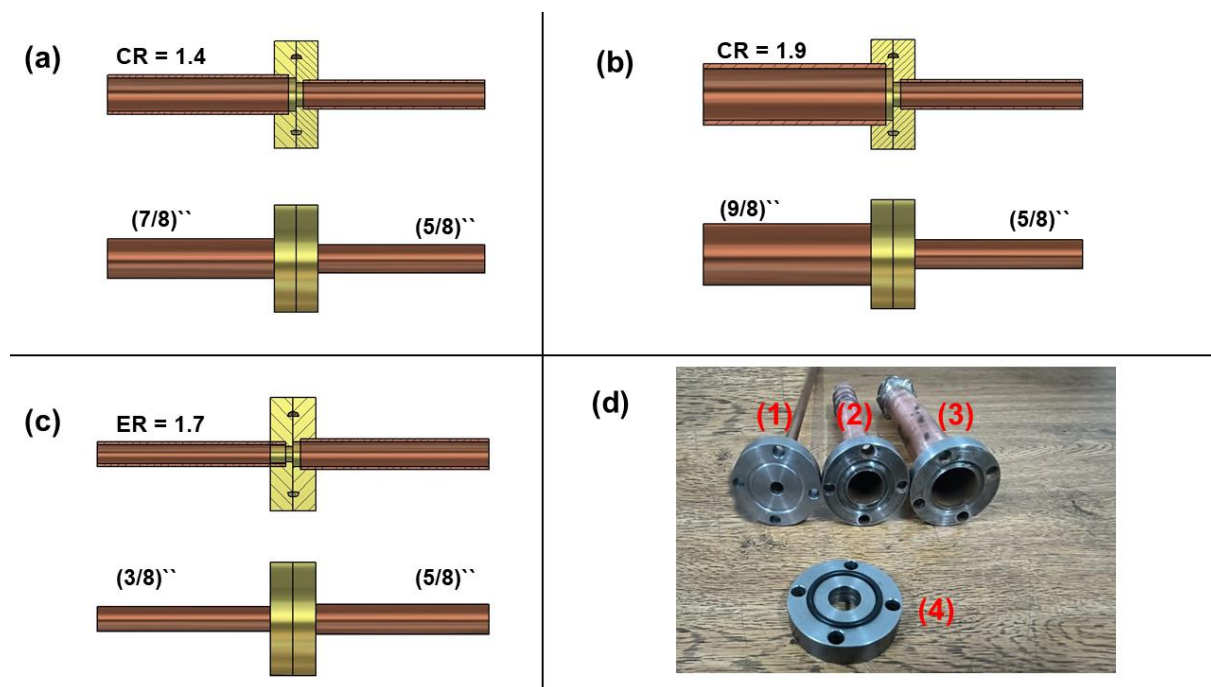


Figure 3.12 – Cross – section of test section during nanofluid flow. (a) CR = 1.4; (b) CR = 1.9; (c) ER = 1.9 and (d) Picture of geometry change parts (1 - Flange with 3/8 - inch; 2 - Flange with 7/8 - inch; Flange with 9/8 - inch; 4 - Flange attached at test section with 5/8 – inch and O - Ring seal). Source: Author's own.

In order to calculate the overall heat transfer rate for nanofluid flowing in circular pipes was adopted the methodology described by Holman (HOLMAN, 2009). The energy equation can be defined as:

$$Q_{nf} = \dot{m}_{nf} \cdot C_{p(nf)} \cdot (T_{out} - T_{in}) \quad (3.5)$$

being $\dot{m}_{nf}$ the nanofluid mass flow rate, $C_{p(nf)}$ nanofluid specific heat, T_{out} nanofluid outlet temperature and T_{in} nanofluid inlet temperature. Convective heat transfer coefficient for each control volume along x-axis at entry region, being defined as:

$$h(x)_{nf} = \frac{q''}{T_s(x) - T_m(x)} \quad (3.6)$$

Where q'' is the applied heat flux in the test section, $T_s(x)$ is the wall temperature along the 'x' distance from the inlet, and $T_m(x)$ the average surface temperature along the test section. To obtain the local wall temperature, 30 T-type thermocouples were positioned along the test section as can be seen in the Fig. (3.13), (**APPENDIX B** shows the calibration curves of the temperature sensors). The $T_m(x)$ can be evaluated using the Eq. (3.7), as follows:

$$T_m(x) = T_{inlet} + \frac{q'' \cdot \pi \cdot D}{\dot{m}_{nf} \cdot C_{p(nf)}} \cdot x \quad (3.7)$$

Where T_{inlet} , D , x , $\dot{m}$ and C_p are respectively the inlet temperature, pipe diameter, axial distance from the entry region, nanofluid mass flow rate and nanofluid specific heat.

For nanofluid flow under contraction twelve flexible tapes-type electrical resistances covered with polyamide were used to apply the heat flux boundary condition at the tube wall, with power ranging from 340 W to 1200 W. For the expansion case two flexible heating tapes OMEGALUX™ STH052 – 120 of fiberglass were attached in the test section. Fig (3.14) presented the heaters attached to the test section in each case investigated.

The electrical power for heating the tube resistors was controlled by a 10 kVA single-phase voltage regulator (Variac) with a peak current of 40 A (Fig. 3.15a). Voltage and current were measured using an ACS712x20A integrated linear current sensor (Fig. 3.15b). Average refrigerant temperatures at the inlet and outlet were recorded by two PT100 three-wire RTD temperature transmitters (Fig. 3.15c). Current and voltage in the resistance circuit were synchronously analyzed using an ammeter and a digital voltmeter. The tube was insulated with a 25 mm glass wool layer (Fig. 3.15d), and the entire test bench was covered with 20 mm elastomeric foam insulation (Fig. 3.15e). Nylon bushings were installed at the tube's inlet and outlet to prevent axial heat leakage (Fig. 3.15f).

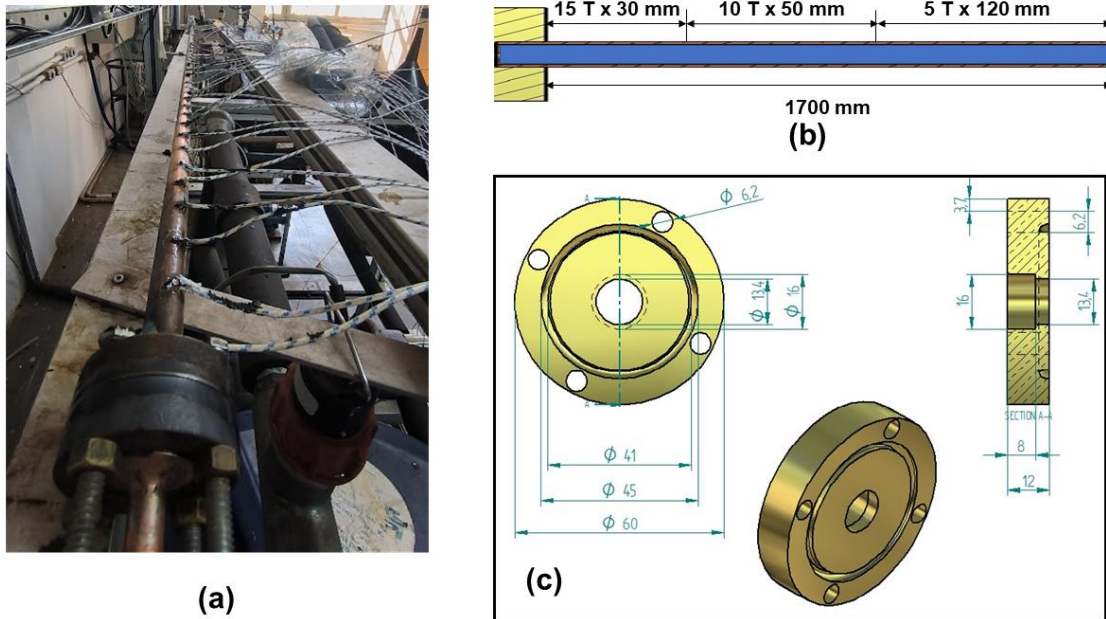


Figure 3.13 – Schematic representation of (a) T-type thermocouples attached to the test section; (b) installation position of the thermocouples in the test section; (c) front view of the flange used to attach the test section to the expansion/contraction section. Source: Author's own.

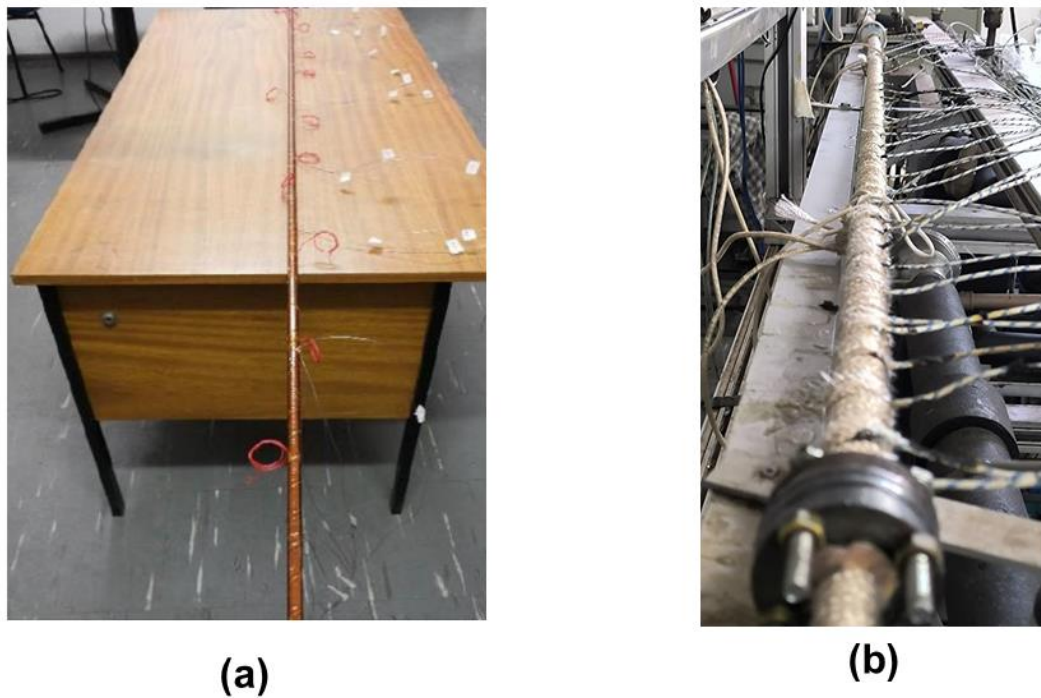


Figure 3.14 – Constructive details of test section. (a) Test section covered with Kapton flexible heaters; (b) Test section covered with Fiberglass heaters. Source: Author's own.

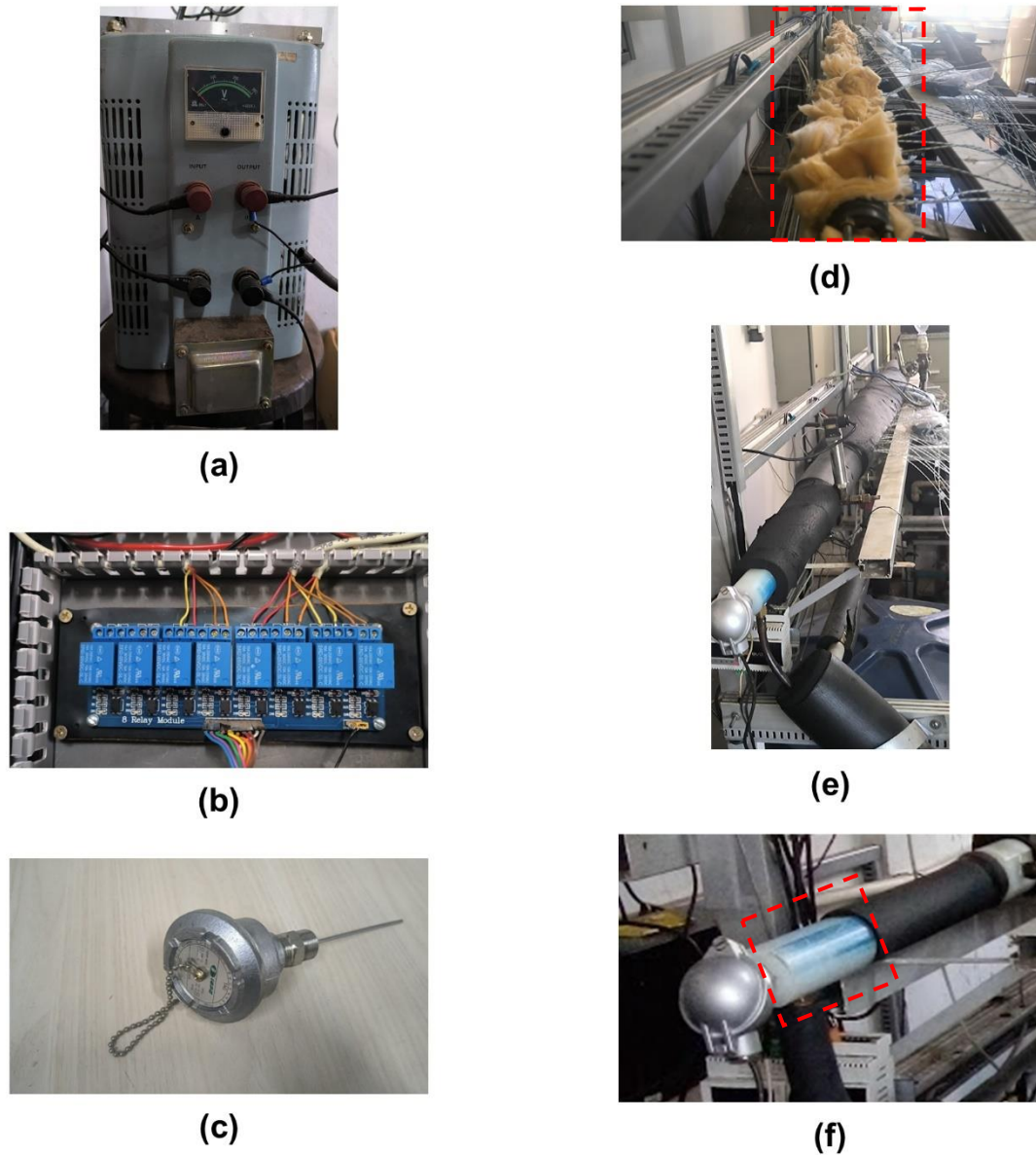


Figure 3.15 – (a) Variac of 10 kVA. (b) Linear current sensor. (c) RTD type PT100. (d) Glass wool insulation covering the test section. (e) Elastomeric foam covering the test section. (f) Nylon bushed at inlet of the test section. Source author's own.

To assess fluid dynamics by measuring pressure drop and calculating the friction factor, two Zurich PSI40 piezoresistive pressure transmitters were installed to monitor gauge pressure at the inlet and outlet of the test section. A differential pressure transmitter, model LD301 (supplied by ESMAR), was also used to measure the pressure drop simultaneously and more accurately across the test section. Nylon components were employed to secure the pressure and temperature measurement instruments to the test section, also functioning as insulators to reduce axial heat loss in the tube. Fig. (3.16a) shows the structural arrangement of the

instrumentation. The test section was thermally insulated with a 25 mm layer of glass wool, followed by an additional 20 mm layer of elastomeric synthetic rubber foam, as shown in Fig. (3.16b).

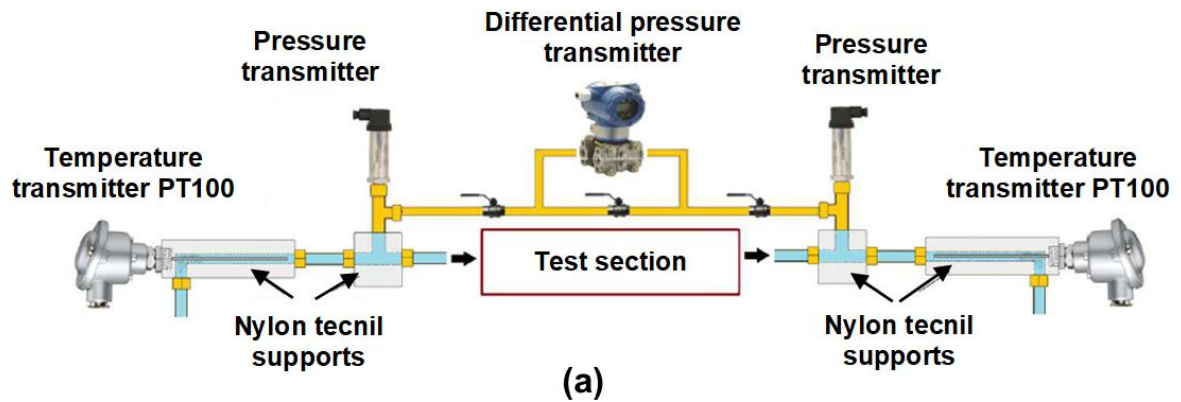


Figure 3.16 – (a) Structural diagram of the installation of measuring instruments in the test section. (b) Insulated test section. Source: Author's own.

3.4.2 Cooling system

The cooling system of the experimental setup was designed to maintain operational conditions by dissipating the heat absorbed by nanofluids in the test section via a heat exchanger. To accommodate the study's focus on testing nanoparticles suspended in a mixture

of water and ethylene glycol, the system underwent modifications. A custom shell-and-tube heat exchanger with five tube passes was designed and implemented.

The system consists of a single-pass shell and five-pass tube heat exchanger, a hydraulic pump, and a cooling tower. The tubes, constructed of thin-walled copper, facilitate the flow of the test fluid. Water circulates through the shell, driven by a hydraulic pump (model B-12 WEG, provided by Thebe 104 Hydraulic Pumps) operating at 3500 RPM with a maximum flow rate of 7 m³/h. The mass flow rate is continuously monitored using a water wheel flow meter (SPX series, Hall effect, supplied by Contech). The heat absorbed by the water is rejected in the cooling tower. A schematic representation of the cooling system is provided in Fig. (3.17).

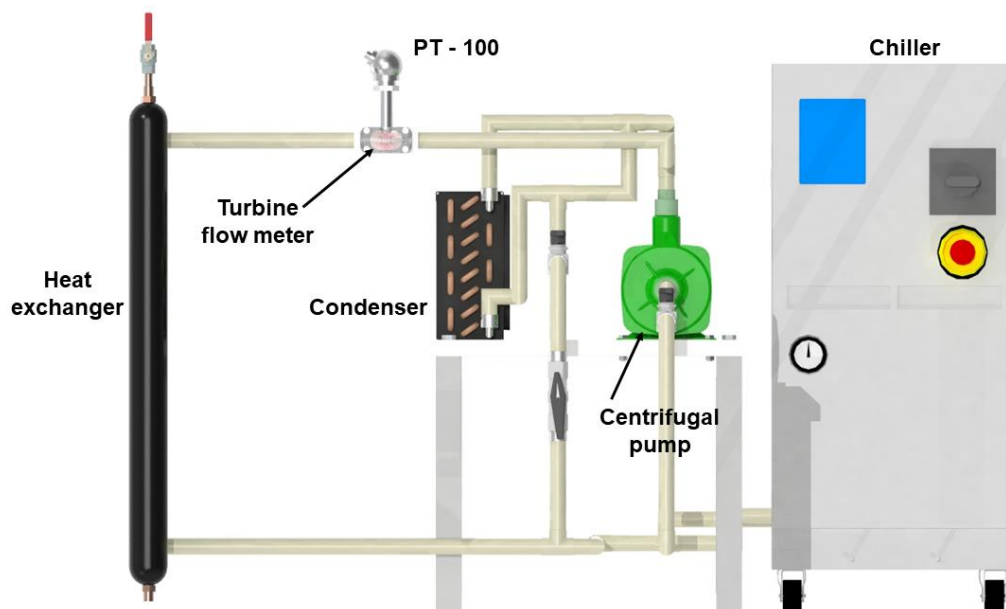


Figure 3.17 – Cooling system schematical representation. Source: Author's own.

3.4.3 Preheating system

Fig. (3.18) illustrates the schematic diagram of the preheating system, which is designed to regulate the fluid temperature at the inlet of the test section. After passing through the test section, the fluid undergoes cooling and loses heat in the flow measurement section, necessitating reheating before re-entering the test section. The preheating process is managed by a circuit comprising a 100 L water reservoir, a centrifugal pump (model ICS-50BV provided by Eletroplas), and a shell-and-tube heat exchanger.

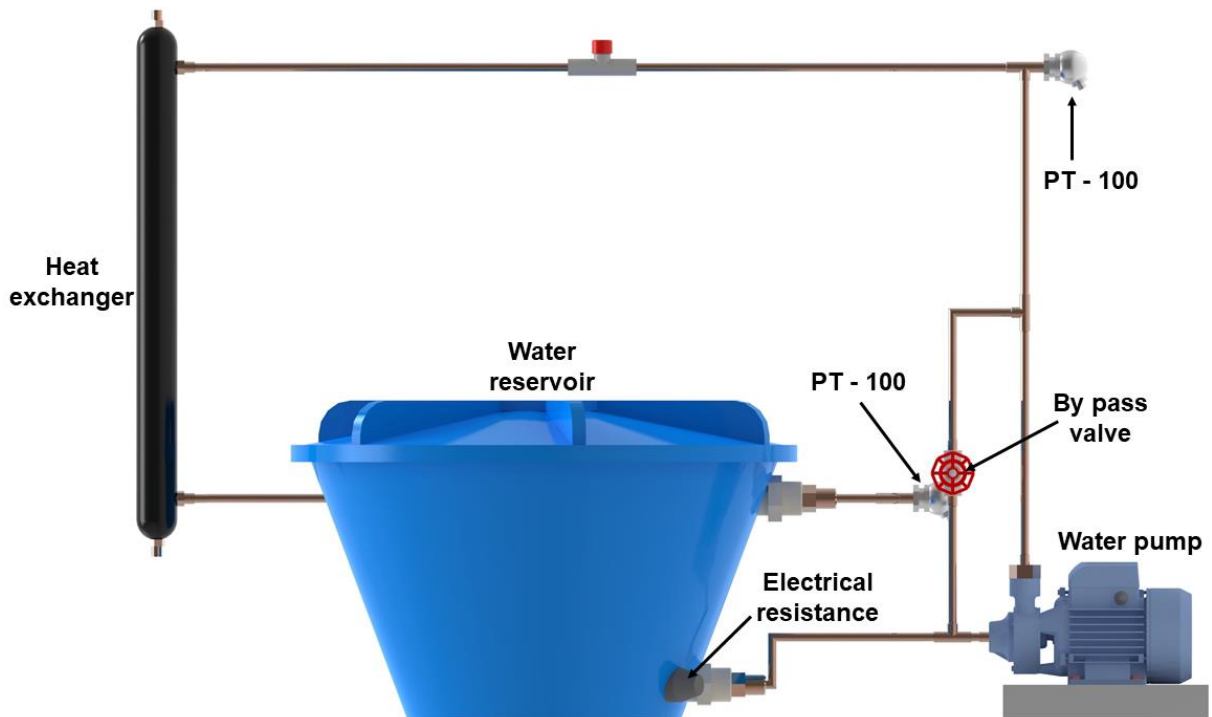


Figure 3.18 – Preheating system representation. Source: Author's own.

The pump operates with a maximum flow rate of 2.1 m³/h, ensuring adequate water circulation throughout the circuit. The water is heated by a 3.5 kW electric resistance element, controlled by a static power converter (model TH6200A16 provided by THERMA), Fig. (3.19). This setup allowed for the development and implementation of a PID temperature control system, achieving an inlet temperature accuracy of ± 0.10 °C relative to the setpoint. Upon exiting the reservoir, the water transfers heat to the test fluid through the shell-and-tube heat exchanger. The test fluid flows within the tubes, while the water circulates through the shell in a countercurrent configuration. Heat transfer is closely monitored using two PT100 temperature sensors installed at the inlet and outlet of the circuit.

In order to achieve the precise test temperatures required for this study, substantial modifications were made to the preheating system. Copper piping was installed throughout the entire hydraulic circuit of the preheating system. This enhancement enabled the reservoir water to be heated efficiently, reaching temperatures of up to 90 °C. The upgraded system ensured stable and accurate thermal conditions, which were critical for the reliability of the experimental results and the overall success of the study.

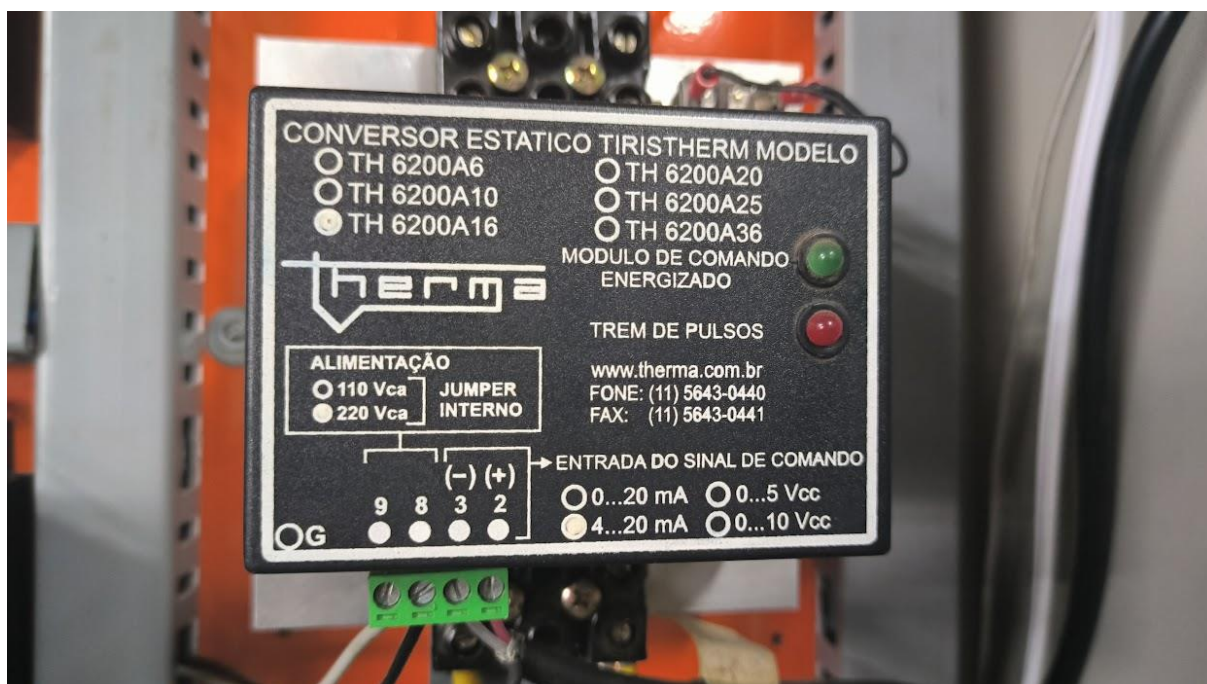


Figure 3.19 – Static power converter TH6200A16. Source: Author's own.

3.4.4 Flow system and mass flow measurement system

The flow and mass flow measurement system are configured with two gear pumps featuring magnetic couplings, two air eliminator valves, and a Coriolis-type mass flow meter, as illustrated in Fig. (3.20).

The main components responsible for maintaining the fluid flow regime in the primary circuit are two gear pumps with magnetic couplings (Fig. 3.20a): one micro pump with a maximum flow rate of 12.8 L/min (Series 4, Model 45, Liquiflo Chemical Processing Pumps Ltd.) and another with a maximum flow rate of 5.68 L/min (Series GK, Model 114/114-56-C, MICROPUMP). Both pumps are mounted in tandem with a 0.5 HP electric motor. Power is supplied through a frequency inverter (Model VLT 2800, Danfoss), which regulates the pump motor speeds. This setup enables the implementation of a PID control system, achieving precise control of the fluid flow rate with an accuracy of ± 0.1 g/s relative to the target mass flow rate setpoint. Additionally, a bypass valve (globe valve) is included to adjust the flow rate for experimental conditions and to provide protection against sudden pressure increases.

The experimental setup also incorporates two air eliminator valves (Fig. 3.20b), installed at elevated positions in the main hydraulic circuit to remove or reduce air bubbles and mitigate undesirable effects on measurement accuracy. The mass flow meter, shown in Fig. 3.20c, consists of a sensor-transmitter assembly. The Coriolis-type sensor (Model RHM06-4F1PS)

and the transmitter (Model CMM01) were provided by METROVAL *Controle de Fluidos Ltda.* This assembly operates within a range of 0.5 to 0.13 kg/min and -20 °C to 117 °C, fulfilling the requirements for the specified nominal testing conditions.



(a)



(b)



(c)

Figure 3.20 – (a) Water pump with magnetic coupling. (b) Air eliminator valve. (c) Coriolis – type mass flow meter. Source: Author's own.

3.4.5 Monitoring and data acquisition system

A data acquisition and monitoring system was developed and assembled for the test bench to record and analyze the desired variables. A graphical interface was built through the LabView® software to obtain and store the data obtained by the instruments installed on the test bench.

The developed monitoring system acquires and stores data from measurement instruments in the experimental setup, focusing on variables needed to assess the thermohydraulic performance of the nanofluid. It also controls the power to the thermal bath heater and the frequency of the magnetic gear pumps to meet test conditions. The control panel, shown in Fig. (3.21), includes alert indicators that activate when discharge pressure or compressor discharge temperature exceeds set limits, when the test fluid temperature drops below 3 °C, or when the mass flow rate falls below 5 g/s. These features ensure precise monitoring and adjustment of testing conditions.

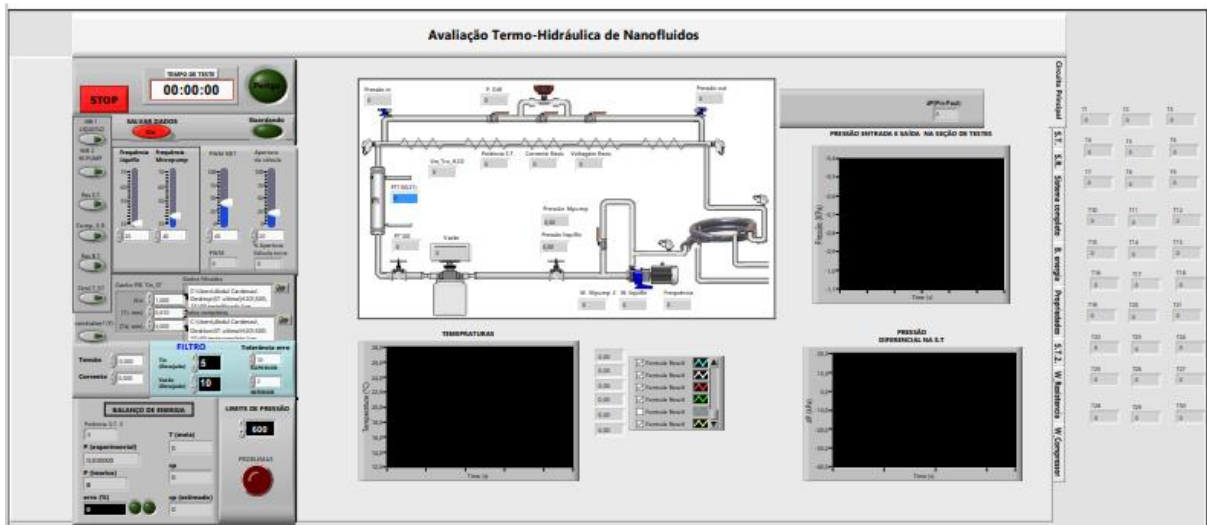


Figure 3.21 – LabView® interface program. Source: Author's own.

The data acquisition system comprises a computer equipped with LabView® programming software and two NI cDAQ-9178 modular system, each featuring 8 slots. This setup is designed for medium-sized portable test systems that capture both physical and electrical signals. The NI cDAQ-9178 chassis supports simultaneous use of up to 8 analog and digital input/output modules, as illustrated in Fig. (3.22).

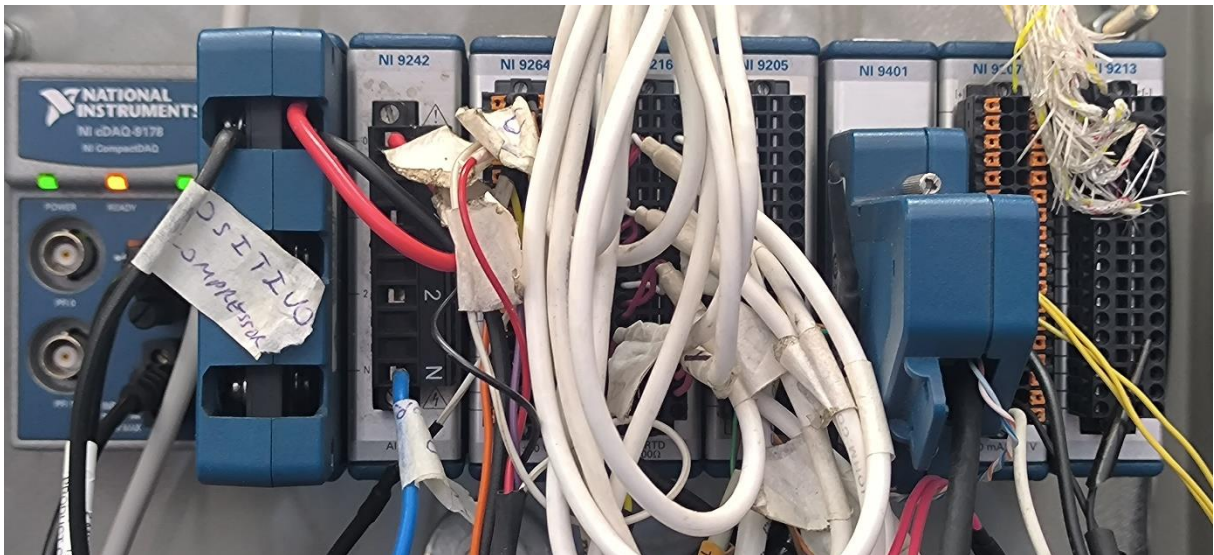


Figure 3.22 – NI cDAQ-9178 modular system used in the data acquisition system. Source: Author's own.

The NI cDAQ-9178 acquisition board transmits conditioned electrical signals from the acquisition modules to the PC. Data are recorded every 5 seconds and stored in a text file in

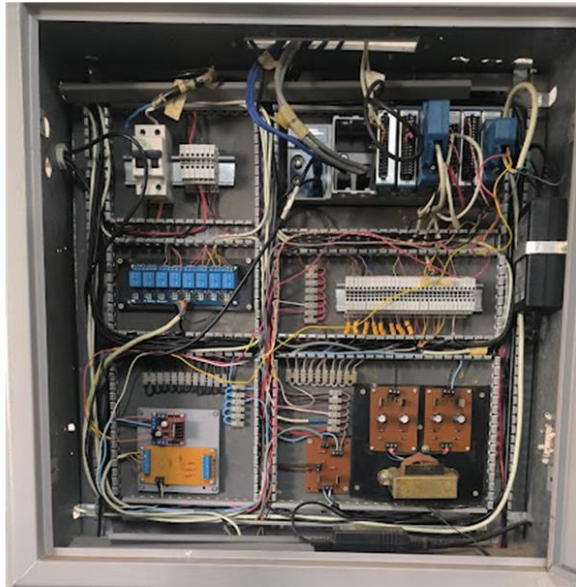
“.txt” format for subsequent processing. Table 3.5 details the instruments and modules employed with the NIcDAQ-9178 chassis to monitor the relevant variables.

Table 3.4 - Modules and instruments that integrate the monitoring system.

Module	Number of Channels	Instrument	Section	Quantity
NI 9214	16	Thermocouple	Test Section	Temperature
NI 9213	16	Thermocouple	Cooling System	Temperature
NI 9216	8	PT100	Test Section Preheated system	Temperature
NI 9203	8	Flow Meter	Flow System	Mass Flow Rate
		Differential pressure transmitter	Test section	Differential pressure
NI 9401	8	Flow Meter	Cooling System	Volumetric Flow Rate
NI 9242	3	voltage regulator (Variac)	Test section	AC Voltage
NI 9246	3	voltage regulator (Variac)	Test section	AC Current
NI 9265	16	Frequency inverter	Flow system	Frequency
		Power controller	Preheated system	Power

Source: Author's own.

The communication between the setup instruments and the computer is facilitated through two electrical panels: one dedicated to data acquisition, depicted in Fig. (3.23a), and another focused on power management, as shown in Fig. (3.23b). These panels are crucial for ensuring the reliable operation of the monitoring system. The final configuration of the experimental setup is illustrated in Fig. (3.24). The operational flowchart of the experimental setup can be found in **APPENDIX C**.



(a)



(b)

Figure 3.23 – Electrical panels. (a) Data acquisition panel. (b) Power panel. Source: Author's own.

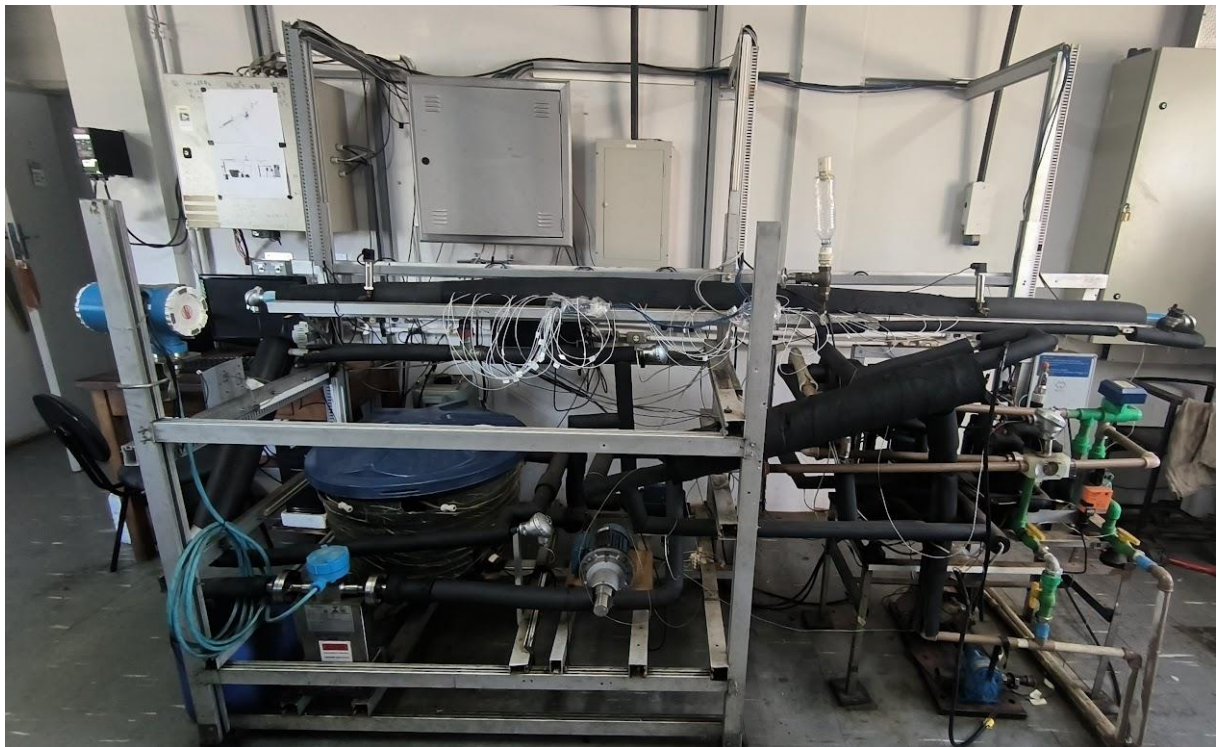


Figure 3.24 – Experimental setup. Source: Author's own.

3.5 Analysis and validation of the experimental setup

During this stage the setup validation was addressed, which was performed using a mixture of water and ethylene glycol 50:50 % in weight (H_2O - EG 50:50 % wt.). This stage aims at knowing the experimental limits of the system's operation, ensure the closure of the energy balance, analyze experimental uncertainties, and select appropriate test conditions. This process is critical for determining the reliability and accuracy of the setup before proceeding with experiments involving more complex fluids like nanofluids.

With the setup fully instrumented and ready for experimentation, the next step involved implementing the methodology to determine the convective heat transfer coefficient and the friction factor. However, before advancing to more complex fluids, the experimental procedure and data analysis were first validated using a distilled water-ethylene glycol mixture (H_2O - EG 50:50 % wt.) as the test fluid, since there is consolidated information in the literature describing their thermohydraulic behavior. The purpose of this validation is to ensure that the experimental equipment can perform, consistently and correctly, all measurements initially for the base fluid and later for the nanofluid.

In the test performed with distilled water-ethylene glycol mixture (H_2O - EG 50:50 % wt.), a volume of 3500 ml was introduced in the experimental bench, being a satisfactory volume, considering the amount of nanofluid required for the tests. The test involved the variation of all parameters to determine the operating range of each. The main objective was to determine a routine to achieve the specific steady-state conditions for each test and thus replicate this routine for the subsequent tests performed with nanofluids. Table 4 describes the nominal conditions established for the tests with distilled water-ethylene glycol mixture.

Additional objectives of the validation process included verifying the absence of leaks, evaluating the operation of the pump with magnetic coupling, and confirming the response of the preheating system. Furthermore, the validation process also involved analyzing the correct operation of data acquisition and storage systems, verifying the functionality and response of the cooling unit, and assessing the accuracy of the mass flow and inlet temperature controllers in the test section. Finally, it was essential to ensure that all electrical resistances responsible for maintaining a constant heat flux within the tube portion of the test section were functioning correctly. These steps were essential for validating the overall performance of the setup and

ensuring that it was fully prepared for conducting more complex experiments involving nanofluids.

Table 3.5 – Conditions for the tests with water-ethylene glycol mixture (H₂O:EG 50:50 wt.%).

Base fluid	Geometry	$\dot{m}$ (kg/s)	Reynolds	T _{inlet}	q" (W/m2)	
H ₂ O:EG 50:50 % wt.	Straight pipe	0.0157	500.4	25 °C		
		0.0394	2500.2			
		0.1574	5000.4			
		0.0093	538.4	45 °C		
		0.0787	2693			
		0.0933	5386			
	CR = 1.4	0.0157	500.4	25 °C		
		0.0236	750.6			
		0.0315	1001			
		0.0394	1251			
		0.0787	2502			
		0.1102	3503			
		0.1574	5004	45 °C		
		CR = 1.9	0.0093			538.4
			0.0140			807.9
			0.0187			1077
			0.0233			1346
			0.0467			2693
	0.0653		3771			
	0.0933	5386	ER = 1.7			
	0.0157	500.4		25 °C		
	0.0236	750.6				
	0.0315	1001				
	0.0394	1251				
	0.0787	2502				
	0.0093	538.4				45 °C
	0.0140	807.9				
	0.0187	1077				
	0.0233	1346				
	0.0467	2693				
	0.0653	3771				
	0.0933	5386				

Source: Author's own.

3.5.1 Energy balance and test section insulation

To validate the energy balance and assess heat loss from the test section to the environment, a comparison was conducted between the electrical power supplied by the heating elements in the test section, denoted as $\dot{Q}_{E.P.}$, and the heat transferred to the test fluids, as determined by the energy balance calculation, $\dot{Q}_{E.B.}$. This comparison was made using the measurements obtained during the experiment and was expressed through Eq. (3.8). The percentage error in the energy balance was then calculated using this equation to quantify any discrepancies.

$$EB = \left[\frac{\dot{Q}_{E.P.} - \dot{Q}_{E.B.}}{\dot{Q}_{E.P.}} \right] \cdot 100 \quad (3.8)$$

Where, $\dot{Q}_{E.P.}$, varied between 340 W and 1100 W as shown in Table 4. Therefore, the average deviation presented for the energy balance in 138 tests performed with the test fluids was less than $\pm 5\%$. Under these conditions, the thermal insulation of the test section proved to be appropriate to avoid significant heat losses. Fig (3.25) presents the validation of energy balance for CR = 1.4, CR = 1.9 and ER = 1.7 performed with H₂O - EG 50:50 % wt. as base fluid with two inlet temperatures 25 °C and 45 °C. **APPENDIX D** shows the energy balance results and friction factor for the straight pipe.

3.5.2 Pressure drop and friction factor

The pressure drop measurement was performed by the difference in the measurements of two pressure transmitters, positioned at the inlet and outlet of the test section. However, the measurements were gauged with the values provided by the differential transducer. It is important to emphasize that the measurements required to determine the fluid dynamic behavior were acquired simultaneously with the thermal tests. The experimental friction factor results were derived from the pressure drop in the test section, as described by Eq. (3.9).

$$f_{exp} = \frac{\pi^2 \cdot D^5 \cdot \rho \cdot \Delta P_{exp}}{8 \cdot \dot{m}^2 \cdot L} \quad (3.9)$$

Thus, the friction factor was evaluated from the results of the tests performed for the water-ethylene glycol mixture flowing inside the test section pipe in laminar and turbulent regimes.

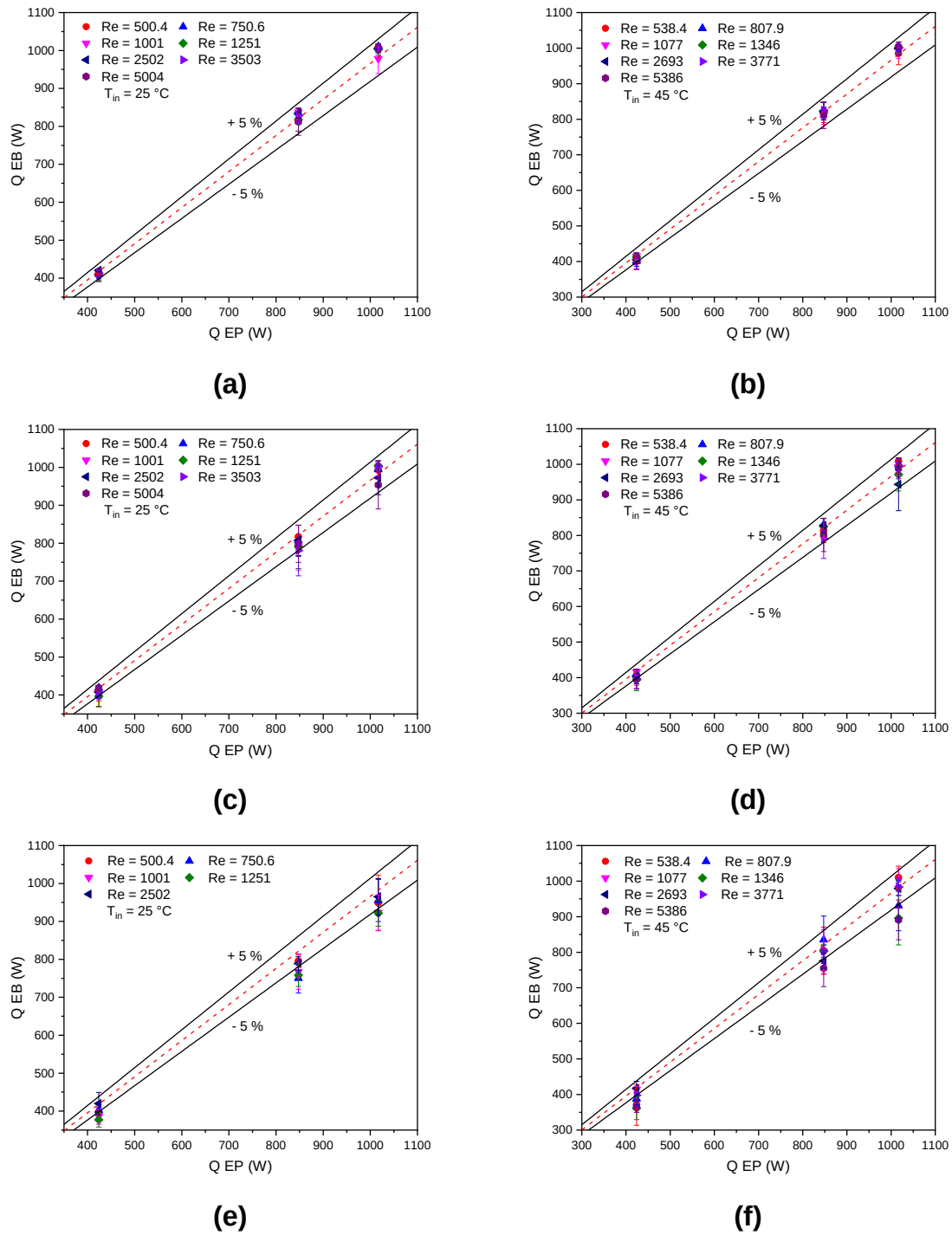


Figure 3.25 – Experimental results for the mixture of water and ethylene glycol relating the electrical power, $\dot{Q}_{E.B.}$, to the power calculated by the energy balance, $\dot{Q}_{E.P.}$ for: (a) $CR = 1.4$ and $T_{in} = 25\text{ }^{\circ}\text{C}$. (b) $CR = 1.4$ and $T_{in} = 45\text{ }^{\circ}\text{C}$. (c) $CR = 1.9$ and $T_{in} = 25\text{ }^{\circ}\text{C}$. (d) $CR = 1.9$ and $T_{in} = 45\text{ }^{\circ}\text{C}$. (e) $ER = 1.7$ and $T_{in} = 25\text{ }^{\circ}\text{C}$. (f) $ER = 1.7$ and $T_{in} = 45\text{ }^{\circ}\text{C}$. Source: Author's own.

The validation is based on a comparison of the results with two correlations, normally used to determine this parameter in laminar and turbulent flow. The experimental results for the friction factor of the test fluids, were compared with the analytical model for laminar regime described in Eq. (3.10). The results were also compared in turbulent regime with the Blasius correlation, described by Eq. (3.11).

$$f = \frac{64}{Re} \quad (3.10)$$

for an application range of $Re \leq 2300$.

$$f = 0.316 \cdot Re^{-1/4} \quad (3.11)$$

for an application range of $Re \leq 10^5$.

The experimental friction factor results across various contraction ratios (CR) and an expansion ratio (ER) reveal significant discrepancies when compared to theoretical predictions, particularly in the laminar flow regime. For contraction ratios of $CR = 1.4$ and $CR = 1.9$, shown in Figs. (3.26a) and (3.26b), the friction factor deviates by $\pm 20\%$ from the laminar model. This deviation is consistent with recent findings that suggest flow disturbances caused by contractions can lead to complex velocity profiles that are not adequately captured by traditional laminar flow equations. For instance, (ZHANG *et al.*, 2022) demonstrated that contractions induce secondary flows and vortices that increase friction losses in microchannel flows, leading to discrepancies in predicted friction factors. In contrast, the turbulent regime shows a much smaller deviation of $\pm 3\%$ from the Blasius correlation, indicating that inertial forces in turbulent flows help stabilize the velocity profile, even in the presence of contractions. This is supported by works such as that by (WANG *et al.*, 2017), which found that in turbulent flow conditions, the effect of geometric changes like contractions is minimized due to the dominance of inertial effects, resulting in a closer match with theoretical models.

Fig. (3.27) highlights a significant deviation in the friction factor for an expansion ratio of $ER = 1.7$ in the laminar regime, much greater than those observed for contraction ratios. This larger deviation can be attributed to the flow separation and recirculation zones commonly associated with expansions, as noted by studies in the literature. (WONG *et al.*, 2015) observed

that expansions in laminar pipe flow led to complex flow behavior, including flow reversal near the walls, which significantly increases frictional losses beyond those predicted by the laminar model. Similarly, (MAHMOOD et al., 2024) emphasized that laminar flow is particularly sensitive to expansions, which can disrupt the flow's parabolic profile and cause substantial deviations from expected friction factors.

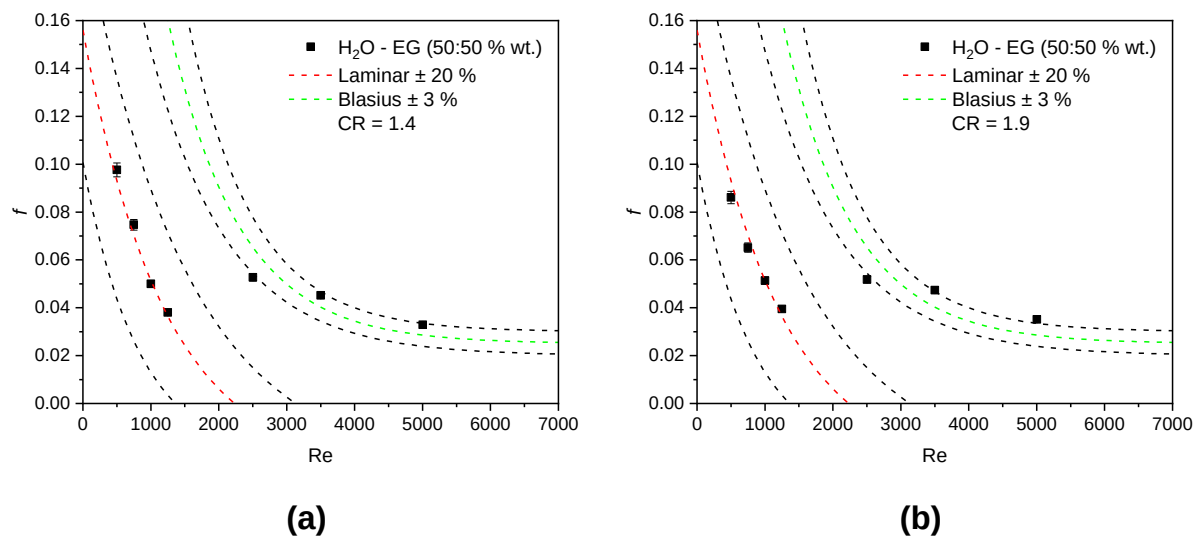


Figure 3.26 – Experimental friction factor versus Reynolds number. Comparison with the Blasius model for turbulent flow and laminar regime for: (a) $CR = 1.4$ and (b) $CR = 1.9$. Source: Author's own.

In the turbulent regime, the effects of expansion are less pronounced, as turbulent mixing quickly dissipates the disturbances caused by the sudden increase in cross-sectional area, leading to a closer alignment with the Blasius correlation. This is consistent with findings by (GÜCÜYEN et al., 2019), who reported that while expansions cause significant deviations in laminar flow, their impact is considerably reduced in turbulent flows due to the high levels of momentum exchange.

In summary, the discrepancies observed in the friction factor for different CRs and ER in laminar flow can be attributed to complex flow disturbances induced by geometric changes, which are not fully accounted for by standard theoretical models. Recent studies in the scientific literature corroborate these findings, highlighting the need for more refined models or empirical adjustments when dealing with flow geometries involving contractions and expansions, particularly in laminar conditions.

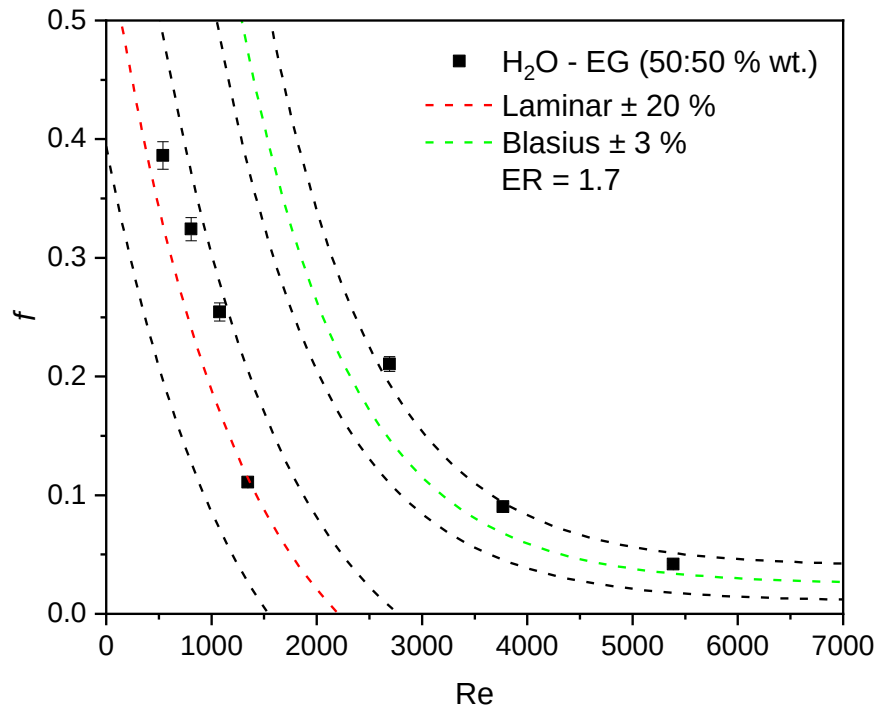


Figure 3.27 – Experimental friction factor versus Reynolds number. Comparison with the Blasius model for turbulent flow and laminar regime for the expansion ratio case (ER = 1.7). Source: Author's own.

3.5.3 Heat transfer coefficient

The average convective heat transfer was determined by the average values computed for the local coefficient along the test section at different measurement points. That is,

$$h_{avg} = \frac{h_{(x_1)} + \dots + h_{(n)}}{n} \quad (3.12)$$

The average Nusselt number then is given as,

$$Nu_{avg} = \frac{h_{avg} \cdot D}{\kappa} \quad (3.13)$$

The Reynolds and Prandtl numbers were given as,

$$Re = \frac{4 \cdot \dot{m}}{\pi \cdot D \cdot \mu} \quad (3.14)$$

$$Pr = \frac{\mu \cdot c_p}{\kappa} \quad (3.15)$$

where the physical properties as thermal conductivity (κ) and, dynamic viscosity (μ) were experimentally obtained. The specific heat was obtained by using the correlation of Eq. (3.4).

A comparison of the experimental data for the base fluid was made with the theoretical models of (SIEDER and TATE, 1936) and (GNIELINSKI, 1975) given by Eq. (3.16) and (3.17) to validate the convective heat transfer in fully developed laminar and turbulent flows. That is, for laminar flows,

$$Nu = 1.86 \cdot \left[\frac{D}{L} \cdot Re_D \cdot Pr \right]^{1/3} \cdot \left(\frac{\mu}{\mu_s} \right)^{0.14} \quad (3.16)$$

For an application range of $0.48 \leq Pr \leq 16700$, $(D/L) \cdot Pr \cdot Re \geq 10$ and $0.0044 \leq (\mu/\mu_s) \leq 9.75$, in laminar flow.

In case of turbulent flows:

$$Nu = \frac{\left(\frac{f}{8} \right) \cdot (Re - 1000) \cdot Pr}{1 + 12.7 \cdot \left(\frac{f}{8} \right)^{1/2} \cdot (Pr^{2/3} - 1)} \quad (3.17)$$

For an application range of $0.5 \leq Pr \leq 2000$, $3000 \leq Re \leq 5 \cdot 10^6$, where the friction factor is defined by Petukhov model, Eq. (3.18)

$$f = (0.79 \cdot \ln(Re) - 1.64)^{-2} \quad (3.18)$$

Figs. (3.28) and (3.29) compare the experimental Nusselt number for H₂O - EG 50:50 % wt. with the Sieder and Tate model for contraction and expansion ratios in laminar flow for contraction ratios of 1.4 and 1.9 (Fig. 3.28), as well as for an expansion ratio of 1.7 (Fig. 3.29), the experimental data exhibit a deviation of approximately ± 20 % from the theoretical model. This indicates that while the Sieder and Tate model provides a reasonable approximation, there are noticeable discrepancies that could stem from experimental uncertainties or the limitations of the model in accurately predicting heat transfer in specific flow configurations.

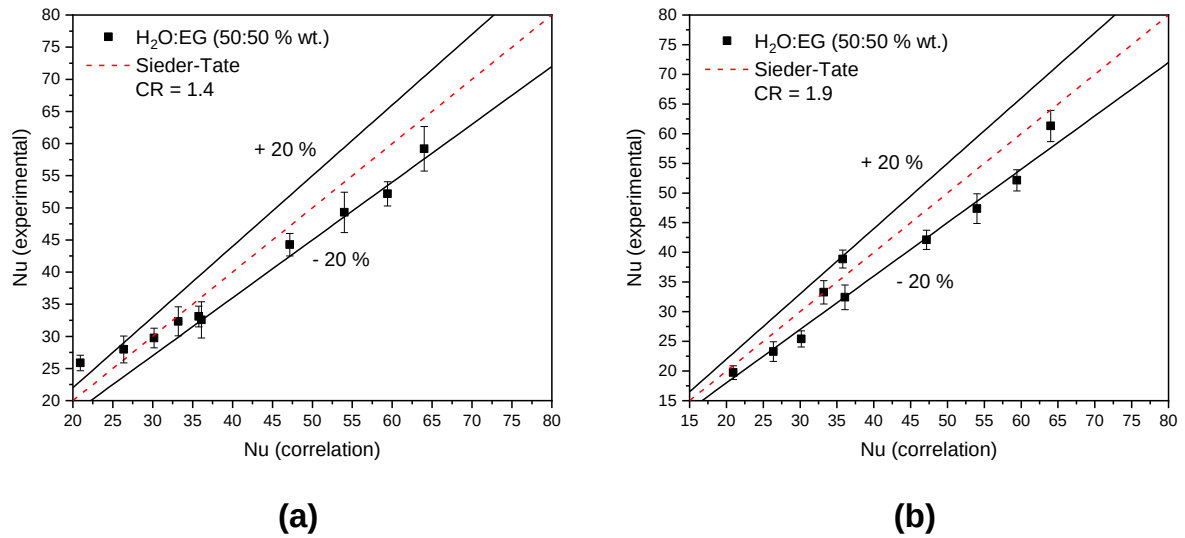


Figure 3.28 – Comparison between the experimental Nu and the correlation of Sieder & Tate for: (a) CR = 1.4 and (b) CR = 1.9. Source: Author's own.

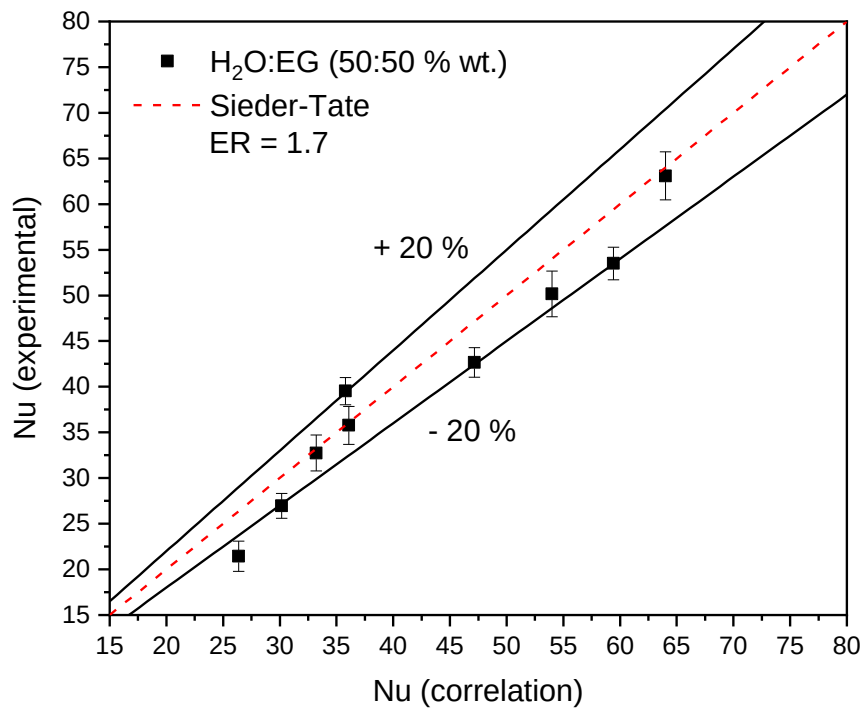


Figure 3.29 – Comparison between the experimental Nu and the correlation of Sieder & Tate for ER = 1.7. Source: Author's own.

Figs. (3.30) and (3.31) compare the experimental Nusselt number with the Gnielinski model for contraction ratios of 1.4 and 1.9 (Figure 3.30) and an expansion ratio of 1.7 (Figure 3.31), the experimental data show a closer alignment with the Gnielinski model, with deviations

of around $\pm 10\%$. This smaller deviation suggests that the Gnielinski model is more effective in capturing the heat transfer characteristics in turbulent flows, making it a more reliable predictor in these conditions. **APPENDIX E** provides the results of the comparison between the laminar and turbulent models for the straight pipe.

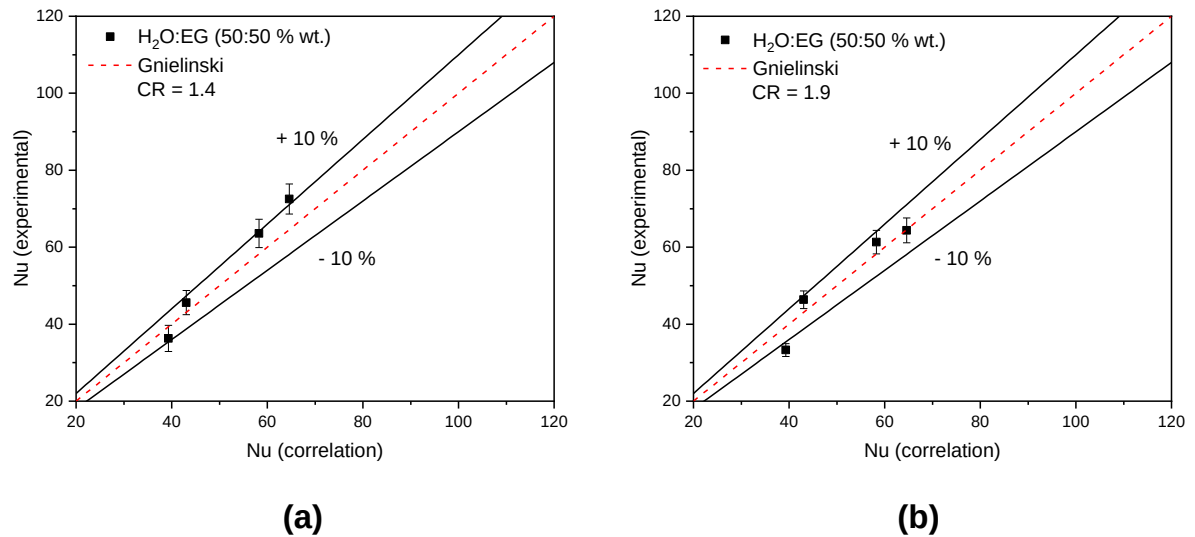


Figure 3.30 – Comparison between the experimental Nu and the Gnielinski model for ER = 1.7.
Source: Author's own.

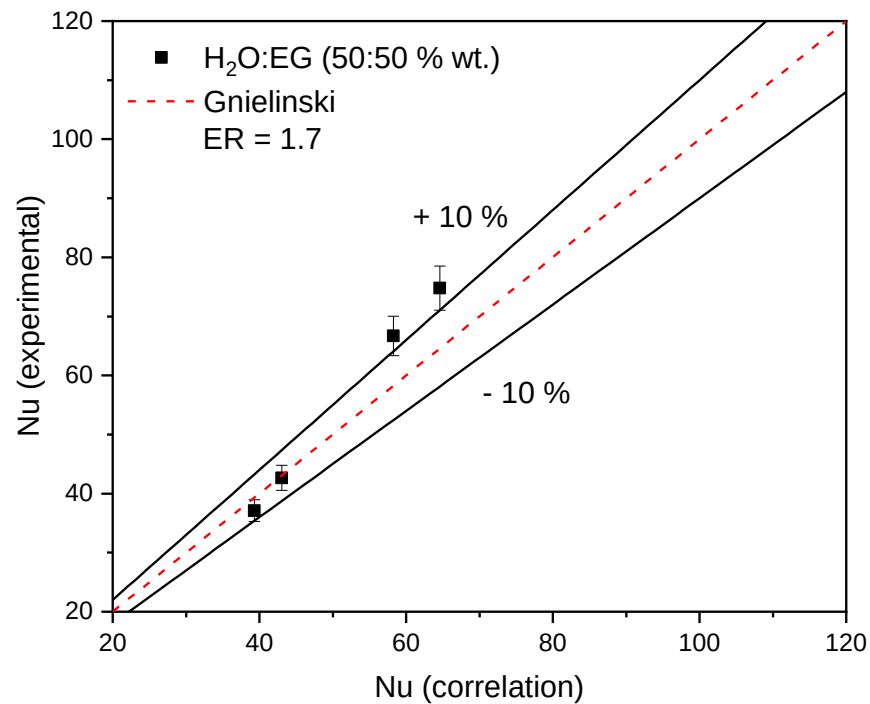


Figure 3.31 – Comparison between the experimental Nu and the Gnielinski model for ER = 1.7.
Source: Author's own.

Overall, the experimental results demonstrate that the Sieder and Tate model can approximate heat transfer in laminar flow with some limitations, while the Gnielinski model provides a more accurate prediction for turbulent flow. The findings validate the use of these models within the tested parameters, with the Gnielinski model showing robustness in turbulent regimes.

3.6 Uncertainties Analysis

The method to estimate the uncertainty of experimental data suggested by (KLINE and MCCLINTOCK, 1953) and (HOLMAN, 2011) was used in the present study. For a group of measured parameters, the uncertainty was determined by the consistent probabilities associated with each measurement, which collectively influence the accuracy of the experimental result. The uncertainty in the results is influenced by the uncertainties present in the initial measurements. Therefore, the result R is a function of the independent variables $x_1, x_2, x_3, \dots, x_n$. Thus:

$$R = R(x_1, x_2, x_3, \dots, x_n) \quad (3.19)$$

In case the uncertainties in the independent variables present the exact probabilities, the uncertainty in the result with these probabilities can be defined as follows:

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{\frac{1}{2}} \quad (3.20)$$

where w_R refers to the uncertainty of the outcome and $w_1, w_2, \dots, w_n$ are the uncertainties of the independent variables such as: Reynolds number, energy balance, power supply, average heat transfer coefficient and Nusselt number. Uncertainties associated with the measured parameters, including the mass flow rate, thermocouples, PT-100 and pressure gauges, were determined based on the specifications provided by the manufacturers.

The measurement variable uncertainties and the propagation of uncertainty to calculated parameters and provided by the manufactures are shown in Table 3.7. The confidence interval adopted for the uncertainties in the independent variables was 95 %. See more details in **APPENDIX F**.

Table 3.6 – Uncertainties of primary and secondary parameters or calculated measurement-dependent variables.

Parameter	Uncertainty
$T_p(n)$	$\pm 0.2\text{ }^{\circ}\text{C}$
$T_{in}\text{ and }T_{out}$	$\pm 0.2\text{ }^{\circ}\text{C}$
$P_{in}\text{ and }P_{out}$	$\pm 0.660\text{ kPa}$
I	$\pm 0.090\text{ A}$
V	$\pm 0.50\text{ V}$
ΔP	$\pm 0.25\text{ \%}$
$\dot{m}$	$\pm 0.15\text{ \%}$
$\dot{Q}_{E.P.}$	$\pm 1.15\text{ \%}$
$\dot{Q}_{E.B.}$	$\pm 4.08\text{ \%}$
q''	$\pm 3.08\text{ \%}$
$\dot{W}_B$	$\pm 0.4\text{ \%}$
$T_m(x)$	$\pm 0.2\text{ }^{\circ}\text{C}$
Re	± 0.21
f	$\pm 0.95\text{ \%}$
h_{avg}	$\pm 10.2\text{ \%}$
Nu_{avg}	$\pm 11.4\text{ \%}$

Source: Author's own.

CHAPTER IV

RESULTS AND DISCUSSION

This chapter presents the results of the study on the thermophysical properties, stability, and thermal performance of graphene and carbon nanotube nanofluids. Various nanoparticle mass concentrations were evaluated under different mass flow rates and temperatures, as outlined in Chapter III of the Methodology.

Results are organized into stability and thermophysical property analysis and thermohydraulic performance evaluation. Discussions are included to elucidate the mechanisms influencing the thermohydraulic performance of nanofluid flow in circular ducts with sudden geometry change, based on existing literature.

4.1 Stability analysis

Nanoparticles inherently tend to aggregate due to their high surface area and surface activity, which leads to challenges in maintaining dispersion stability. Stabilization, typically achieved through sonication, is crucial to prevent agglomeration. However, the strong van der Waals forces between particles present a persistent challenge in achieving stable nanoparticle suspensions, as these forces promote easy aggregation within the nanoparticles (DAS *et al.*, 2024). To overcome this problem, several researchers have implemented surfactants to modify nanofluids' pH or isoelectric point, thereby increasing the nanofluid efficiency with higher particle dispersion (GARCÍA-RINCÓN and FLORES-PRIETO, 2024).

In this study, nanofluids were synthesized using a standard solution and commercially available nanoparticle powder. A high-concentration graphene solution was obtained and subsequently diluted to achieve the target concentrations. In the case of industrial graphene in

pasta, small fractions were mixed in the base fluid to obtain the desired concentrations. For carbon nanotubes in powder form, surface treatment with oleic acid was employed to enhance dispersion in the base fluid. Additionally, ultrasonication was applied to break up agglomerates and improve nanoparticle dispersion in the base fluid.

After synthesizing the nanofluids, samples were collected in 50 ml Falcon tubes (Fig. 4.1) and stored in various cuvettes for a two-stage stability evaluation. The first stage involved a visual assessment to detect rapid nanoparticle sedimentation. If no sedimentation occurred within 24 hours, the second stage proceeded with a quantitative analysis using UV-VIS spectrophotometry, as detailed in section 3.2, utilizing the SHIMADZU UV-1900 spectrophotometer.

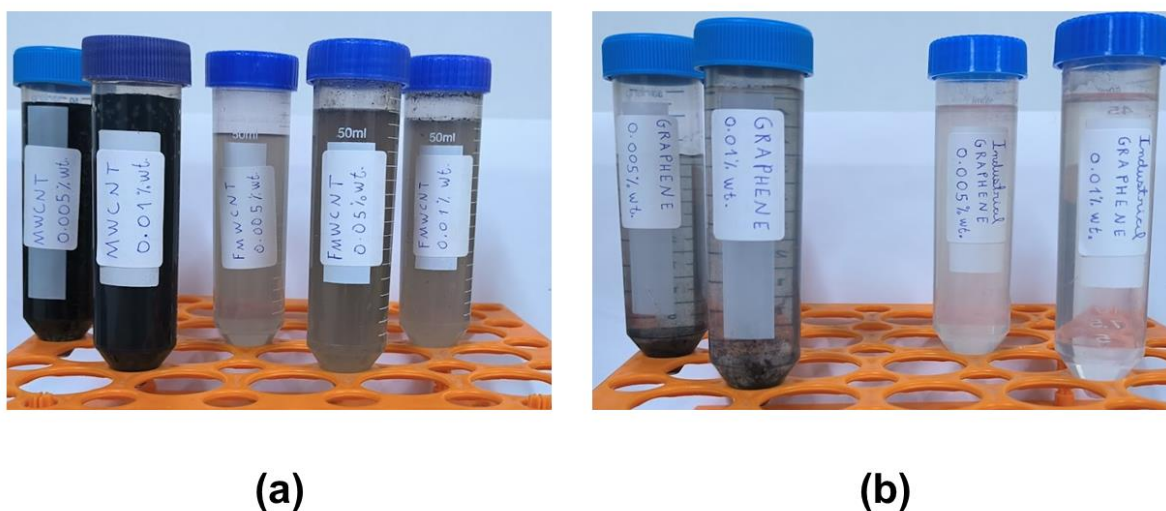


Figure 4.1 – Nanofluids samples separate for visual stability inspection. (a) Carbon nanotubes, (b) Graphene. Source: Author's own.

The carbon nanotube samples were diluted at a 1:40 ratio with the base fluid before analysis to prevent interference from their dark color. This ensured accurate absorbance readings without saturating the spectrophotometer's measurement range. All measurements were performed at room temperature, between 25 °C and 30 °C. Fig. (4.2b and 4.3d) presents the results of UV-VIS spectroscopy for MWCNT and FMWCNT using the 400 nm wavelength as a reference for the relative mass concentration, derived from linear regression analyses based on the data from Fig. (4.2a and 4.2c), across various measurement times (see **APPENDIX G**). The same analysis for graphene and industrial graphene is presented in Fig. (4.3).

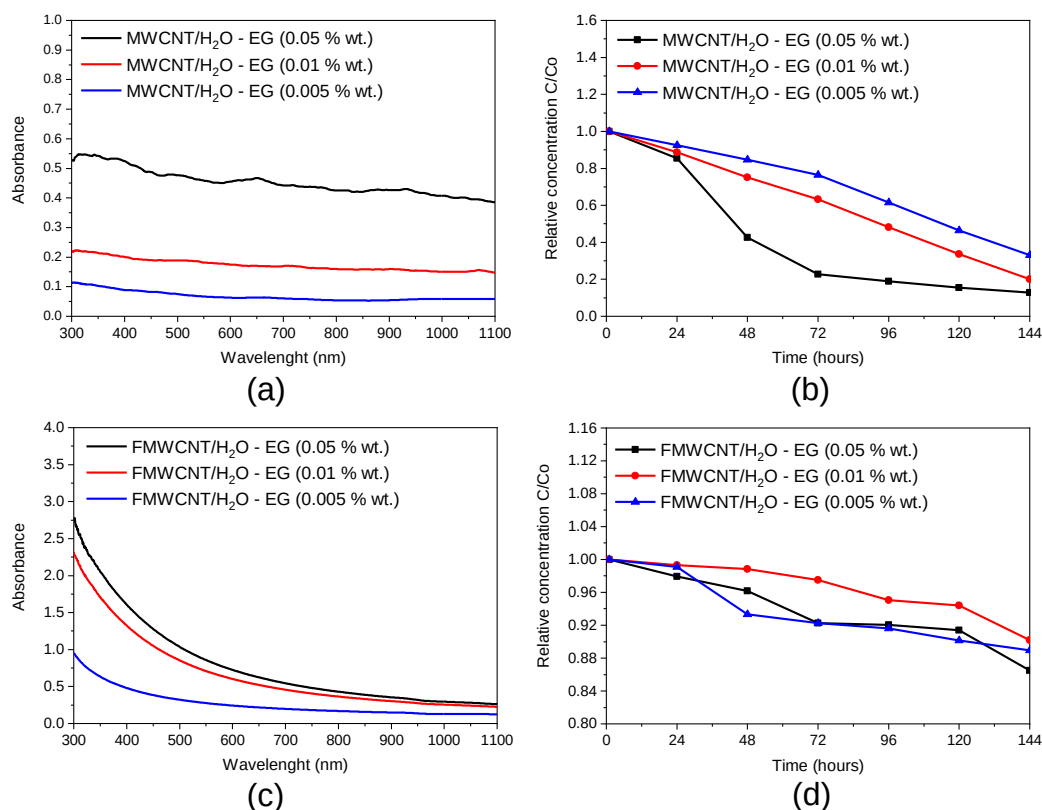


Figure 4.2 – Absorbance versus wavelength for (a) MWCNT/H₂O-EG and (c) FMWCNT/H₂O-EG samples, and concentration over time for (b) MWCNT/H₂O-EG and (d) FMWCNT/H₂O-EG nanofluids. Source: Author's own.

In Fig (4.2a), the absorbance spectra for MWCNT nanofluids across a wavelength range of 300 nm – 1100 nm show relatively low values for all concentrations, indicating limited initial dispersion and stability. The higher concentration (0.05 % wt.) exhibits slightly higher absorbance, suggesting a greater presence of dispersed nanoparticles, although the values remain low. The near - constant absorbance across the wavelength range suggests minimal sedimentation within the measurement period. Conversely, the absorbance spectra for FMWCNT nanofluids, shown in Fig. (4.2c), are significantly higher, especially at the beginning of the measurement. This indicates that functionalization with oleic acid greatly enhanced the dispersion of MWCNTs in the H₂O-EG mixture. However, a steep decline in absorbance with increasing wavelength, particularly for the higher concentration, implies that some sedimentation may still occur despite the improved initial dispersion. During seven days, the minimum values for the lowest relative concentration for MWCNT and FMWCNT were respectively 0.43 and 0.87, as can be seen in Fig (4.2b) and Fig. (4.2d), indicating a reasonable

stability for the analyzed samples due to the amount of nanoparticles remaining dispersed in the base fluid after the analyzed period. Seven days after the preparation, the nanofluids showed satisfactory colloidal stability, highlighted for the FMWCT/H₂O-EG sample with 0.05 %, 0.01 % and 0.005 % weight fraction, which exhibited the best stability and the lowest sedimentation rates results of 11 %, 10 % and 13 %, respectively.

In Fig. (4.3), similar analyses are conducted for graphene and industrial graphene-based nanofluids. The absorbance spectra for graphene nanofluids (Fig. 4.3a) are relatively low and nearly constant across the wavelength range, indicating poor initial dispersion and stability. The higher concentration (0.05 % wt.) shows slightly higher absorbance, but the differences are minimal. The industrial graphene nanofluids (Fig. 4.3c) exhibit much higher initial absorbance, particularly for the higher concentration, suggesting better initial dispersion. However, the steep decrease in absorbance across wavelengths suggests significant sedimentation even during the measurement period, especially for the higher concentration.

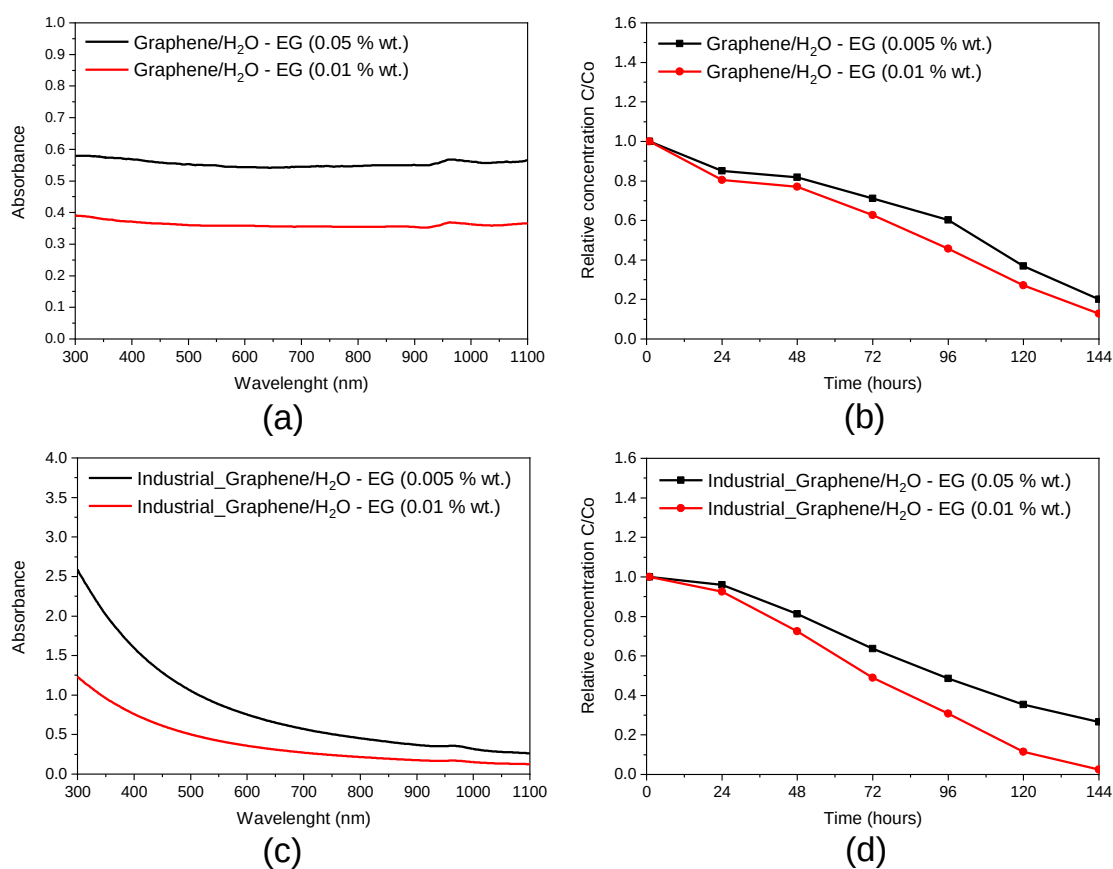


Figure 4.3 – Absorbance versus wavelength for (a) Graphene/H₂O-EG and (c) Industrial graphene/H₂O-EG samples, and concentration over time for (b) Graphene/H₂O-EG and (d) Industrial graphene /H₂O-EG nanofluids. Source: Author's own.

The time-dependent relative concentration data for graphene nanofluids, shown in Fig. (4.3b) and Fig. (4.3d), reveal a steady decline in stability over seven days. For graphene nanofluids (Fig. 4.3b), the higher concentration (0.05 % wt.) drops to approximately 18 % of its initial concentration, while the lower concentration (0.005 % wt.) retains about 30 % after seven days, indicating significant sedimentation over time. The industrial graphene nanofluids (Fig. 4.3d) show an even sharper decline, with the highest concentration almost completely sedimented and the lowest concentration retaining around 20 % of its initial concentration after seven days. These results indicate poor long-term stability, particularly for industrial graphene, despite its higher initial absorbance.

The stability results emphasized the significant role of nanoparticle surface treatment and concentration in determining nanofluid stability. Functionalization, as demonstrated with FMWCNTs, is crucial for enhancing stability by reducing agglomeration and sedimentation, particularly at higher concentrations. In contrast, both graphene and industrial graphene-based nanofluids display considerable sedimentation, with industrial graphene exhibiting the least stability. These findings emphasize the need for optimizing nanoparticle surface treatment and concentration to ensure the long-term stability and effectiveness of nanofluids in practical applications as suggested by (CHEN *et al.*, 2024; DAN *et al.*, 2024; DAS *et al.*, 2022a, 2022b).

4.2 Thermophysical properties

Accurate prediction of heat transfer behavior in nanofluids requires a thorough understanding of their thermophysical properties. The inclusion of nanoparticles, which possess distinct thermophysical characteristics, significantly alters the properties of conventional working fluids. Key thermophysical properties such as thermal conductivity, viscosity, specific heat capacity, and density are notably influenced by the addition of nanoparticles (SAID *et al.*, 2022). These changes directly affect convective heat transfer. The thermophysical properties of nanofluids are determined by factors including nanoparticle size, shape, concentration, type, and the properties of the base fluid (KALSI *et al.*, 2023). This section presents the experimental results of the thermophysical properties of the prepared nanofluids, with data analyzed as a function of temperature and concentration, the primary factors affecting viscosity and thermal conductivity as identified in the literature.

4.2.1 Thermal conductivity

Thermal conductivity measurements were conducted using the LINSEIS THB-1 model, utilizing the hot transient bridge technique. This technique enables the measurement of thermal conductivity, thermal diffusivity, and specific heat of a wide range of materials, including solids, liquids, powders, and pastes.

The measurements were carried out automatically using the software provided by the manufacturer, with 10 measurements per cycle and 2 to 3 cycles per sample. The temperature range employed for the measurements was from 30 °C to 50 °C.

Fig. (4.4a) and Fig. (4.4b) depict the results obtained for thermal conductivity increments for MWCNT and FMWCNT samples respectively as a function of the different temperatures at which the measurements were taken.

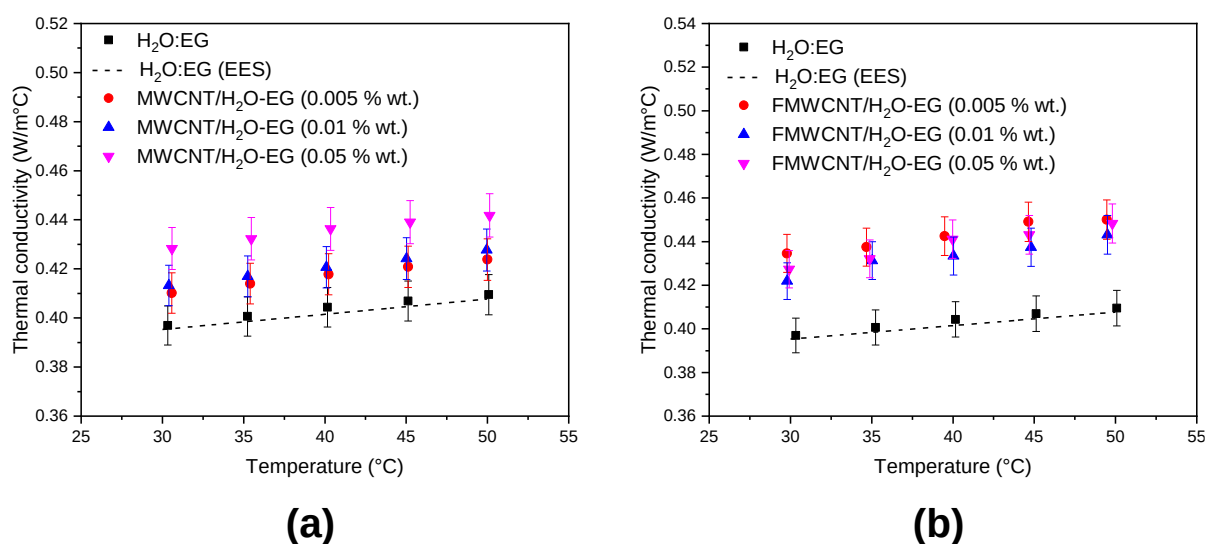


Figure 4.4 – Experimental results for Thermal conductivity of nanofluid samples and base fluid. (a) MWCNT/H₂O:EG. (b) FMWCNT/H₂O:EG. Source: Author's own.

The average increments obtained for nanofluid samples of carbon nanotubes were, on average, 3.37 %, 4.17 % and 7.89 % for MWCNT/H₂O-EG samples (Fig. 4.4a), and 9.67 %, 7.61 %, 8.58 % for FMWCNT/H₂O-EG samples (Fig. 4.4b), for the nanoparticle concentrations of 0.005 % wt., 0.01 % wt. and 0.05 % wt. respectively. The superior performance of FMWCNTs underscores the effectiveness of surface treatment with oleic acid in boosting thermal conductivity.

In contrast, nanofluid samples based on graphene exhibited the highest increments in thermal conductivity compared to the base fluid relative to the MWCNT samples as can be seen in Fig (4.5a) and Fig. (4.5b). The average increases were 8.24 % and 9.08 % for nanofluid samples of graphene with mass concentrations of 0.005 % and 0.01 % respectively. For industrial graphene samples the average increases for the mass concentrations of 0.005 % and 0.01 % were respectively 6.26 % and 7.74 %.

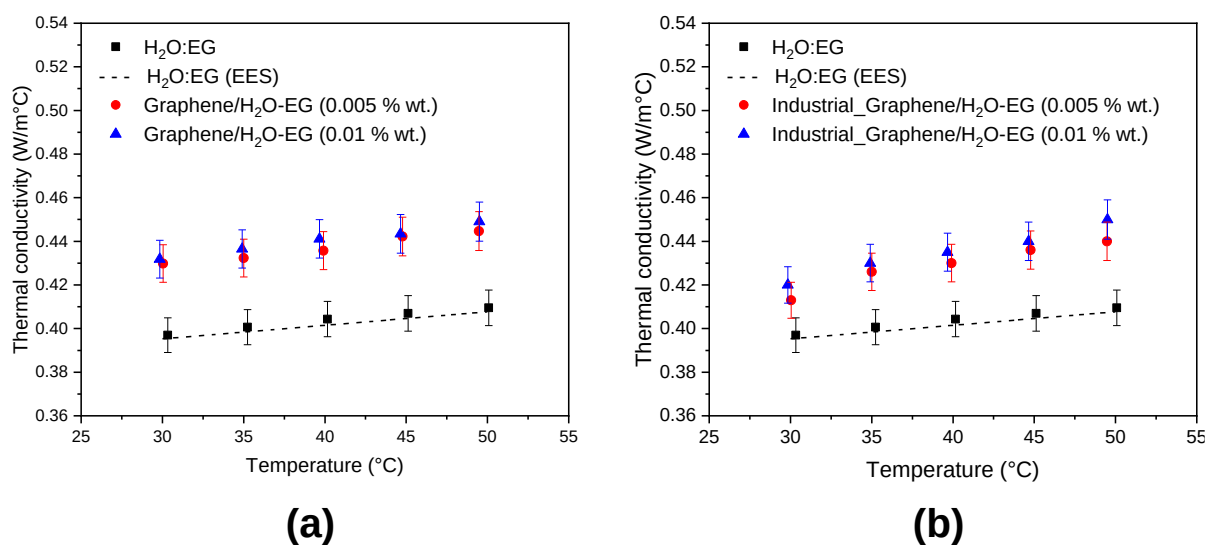


Figure 4.5 – Experimental results for Thermal conductivity of nanofluid samples and base fluid. (a) Graphene/H₂O:EG. (b) Industrial graphene/H₂O:EG. Source: Author's own.

The thermal conductivity analysis of different nanofluids, as presented in Fig. (4.4) and Fig. (4.5), reveals significant variations in performance based on nanoparticle type, surface treatment, and concentration. In Fig (4.4a) and Fig (4.4b), the MWCNT/H₂O-EG and FMWCNT/H₂O-EG nanofluids exhibit varying degrees of thermal conductivity enhancement based on nanoparticle concentration and surface treatment. MWCNT nanofluids showed moderate increases in thermal conductivity, with higher concentrations leading to greater enhancements. FMWCNT nanofluids, which benefit from surface functionalization, demonstrated even higher thermal conductivity improvements, particularly at lower concentrations. This aligns with recent studies, such as those by (ISA *et al.*, 2020; KARIMI BAKHTIYAR *et al.*, 2022), which emphasize that functionalization significantly improves thermal conductivity by enhancing nanoparticle dispersion and reducing agglomeration, thereby facilitating better heat transfer performance.

Fig. (4.5a) and Fig. (4.5b) illustrate the thermal conductivity performance of graphene-based nanofluids. The results show that graphene/H₂O-EG nanofluids achieved the highest increases in thermal conductivity, with industrial graphene nanofluids performing slightly less effectively. These findings are supported by recent research, including work by (ELSAID *et al.*, 2021; KARIMI BAKHTIYAR *et al.*, 2022), which highlights the superior thermal properties of graphene due to its high surface area and excellent thermal conductivity. However, the slight reduction in performance for industrial graphene could be attributed to potential impurities or defects introduced during industrial processing, as reported by (AHMAD *et al.*, 2021).

These results highlight the importance of nanoparticle type, surface treatment, and concentration in determining the thermal conductivity of nanofluids. Functionalized MWCNTs and graphene-based nanofluids, particularly at higher concentrations, exhibit superior thermal performance, making them promising candidates for enhancing heat transfer in various industrial applications.

4.2.2 Dynamic viscosity

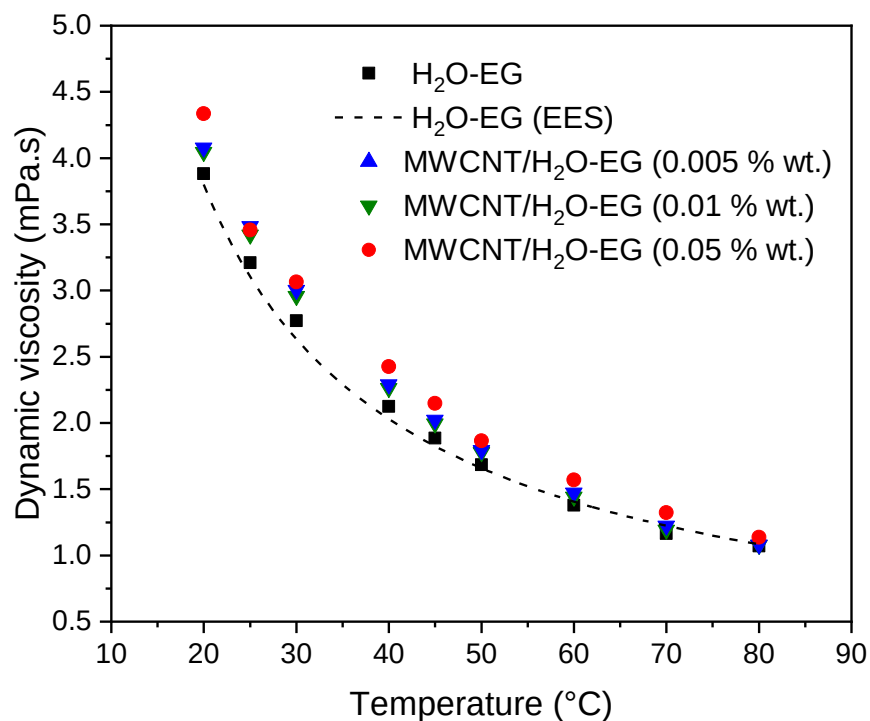
The dynamic viscosity, as well as the density, of the nanofluid samples were measured using the StabingerTM SVMTM 3000 viscometer from Anton Paar. Fig. (4.6a - 4.6d) depict the results of dynamic viscosity for nanofluid samples across a temperature range of 20 °C up to 80 °C.

The viscosity increments obtained for nanofluid samples of carbon nanotubes were, on average, 4.76 %, 6.25 % and 10.48 % for MWCNT/H₂O-EG samples, and 7.89 %, 8.68 % and 13.16 % for FMWCNT/H₂O-EG samples, for nanoparticle concentrations of 0.005 % wt., 0.01 % wt. and 0.05 % wt. respectively.

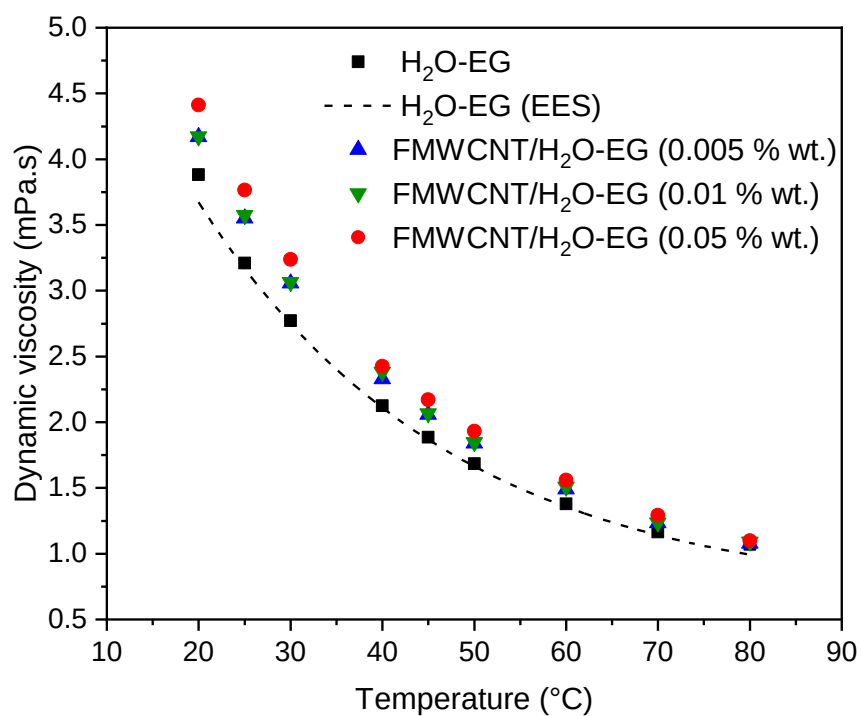
In the case of graphene-based nanofluid samples, the increase in viscosity averaged 0.7 % and 2.9 % for samples with mass concentrations of 0.005 % and 0.01 % respectively, compared to the base fluid. For industrial graphene samples, the increases in viscosity in relation to the base fluid were on average 8.1 % and 9.72 % for nanoparticle concentrations of 0.005 % wt. and 0.01 % wt. respectively.

Fig. (4.6a) and Fig. (4.6b) show increasing viscosity in MWCNT and FMWCNT nanofluids with higher nanoparticle concentrations. This trend is supported by studies, such as (MOHAMMAD *et al.*, 2022), which highlight that nanoparticle addition enhances viscosity

through increased particle-fluid interactions, and surface functionalization, such as FMWCNTs, further improves dispersion and viscosity.



(a)



(b)

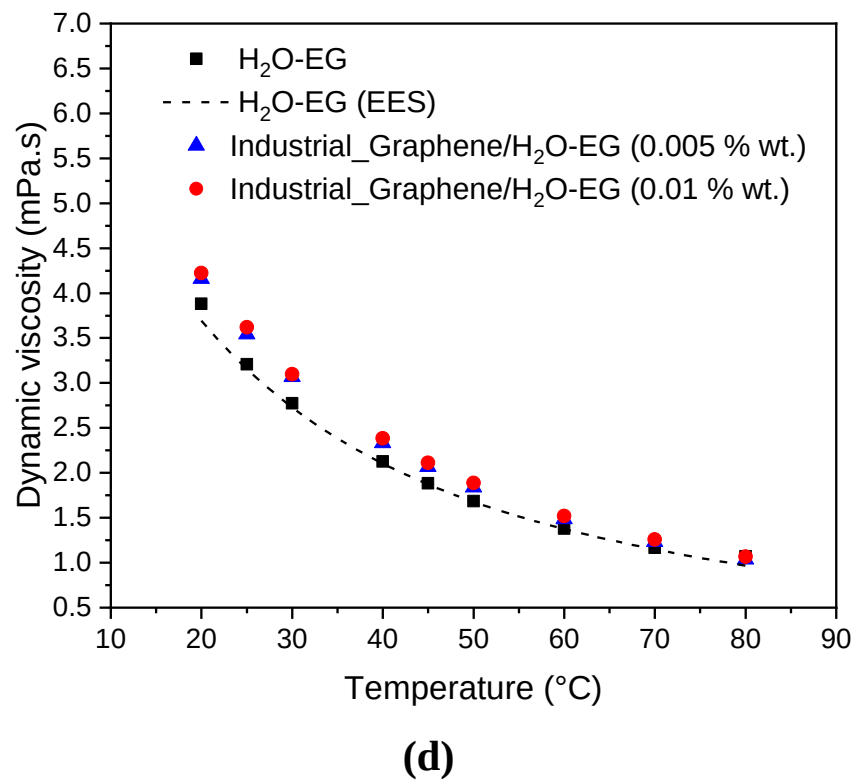
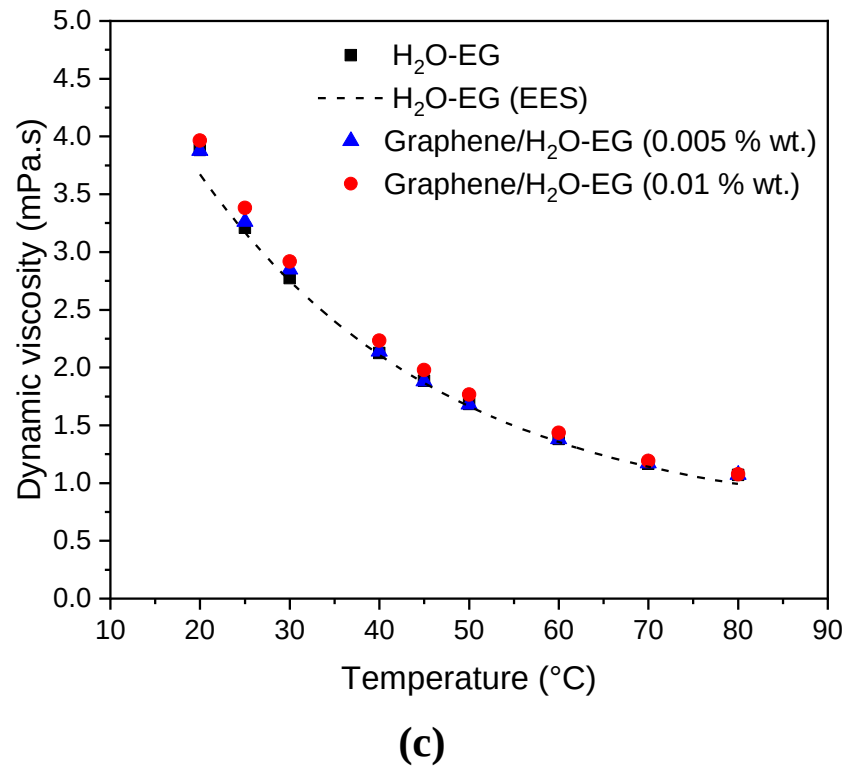


Figure 4.6 – Experimental results for dynamic viscosity of nanofluid samples and base fluid. (a) MWCNT/H₂O:EG. (b) FMWCNT/H₂O:EG. (c) Graphene/H₂O:EG. (d) Industrial graphene/H₂O:EG. Source: Author's own.

Fig. (4.6c) and (4.6d) show that graphene nanofluids exhibit a lower viscosity increase than MWCNT-based fluids, due to graphene's two-dimensional structure, which minimize fluid flow disruptions. However, industrial graphene samples show higher viscosity, likely from impurities or aggregation that elevate flow resistance. According (DONG et al., 2021; HAMZE et al., 2021; LE BA et al., 2020) the impact of graphene on viscosity is modest unless aggregation occurs, as seen with industrial graphene.

Fig. (4.7) indicates that the dynamic viscosity of nanofluids generally increases with higher concentrations of solid nanoparticles. (APMANN *et al.*, 2021a) found that increasing nanoparticle concentration enhances both thermal conductivity and viscosity, while larger nanoparticle sizes reduce viscosity but may either increase or decrease thermal conductivity. Surfactants can increase thermal conductivity at low concentrations but reduce it at higher levels, while also decreasing viscosity. (GANESH KUMAR *et al.*, 2019; HAMZE *et al.*, 2021) observed significant viscosity increases with higher nanoparticle concentrations, highlighting the influence of concentration, surfactant type, and preparation methods. (MUKHERJEE *et al.*, 2024) emphasized the role of stability, noting that agglomeration and sedimentation can impact viscosity.

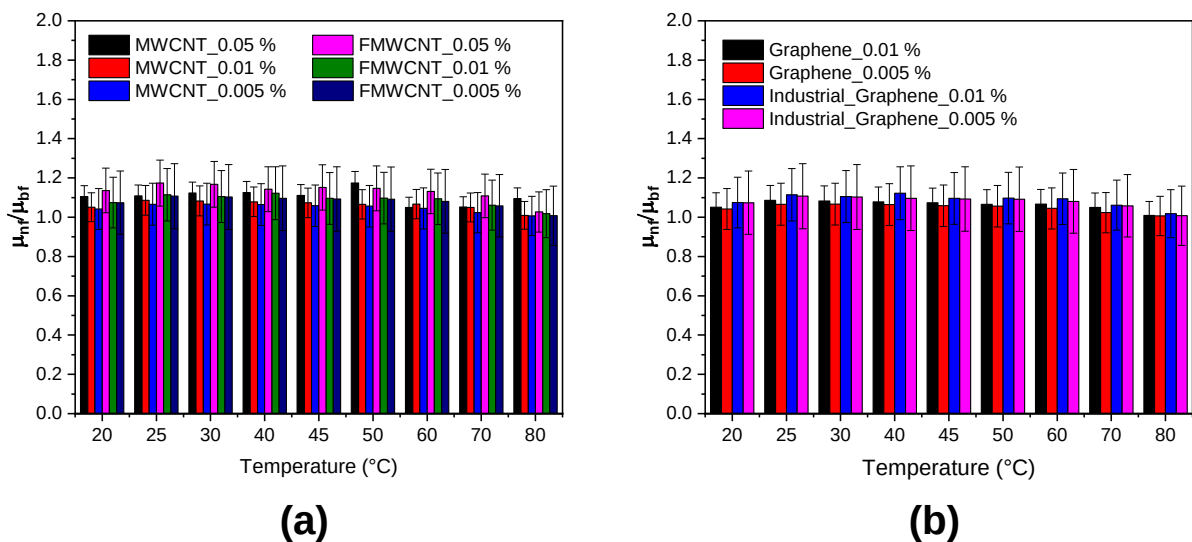


Figure 4.7 – Relative viscosity of nanofluids samples of: (a) Carbon nanotubes. (b) Graphene. Source: Author's own.

These findings indicate that, initially, increased pumping power is necessary to facilitate the flow of nanofluids. Moreover, the sensitivity of these nanofluids to temperature variations is a significant factor in comprehending their behavior in practical applications.

4.2.3 Density

Experimental data on density were obtained using a rotational viscometer, specifically the StabingerTM SVMTM 3000 model from Anton Paar. This viscometer features a cylindrical geometry with concentric tubes and a controlled temperature range of 20 °C to 80 °C. During the experiment, samples were injected into the equipment, and density measurements were conducted using a speed rotor. Additionally, the equipment provided data on dynamic viscosity and specific mass values.

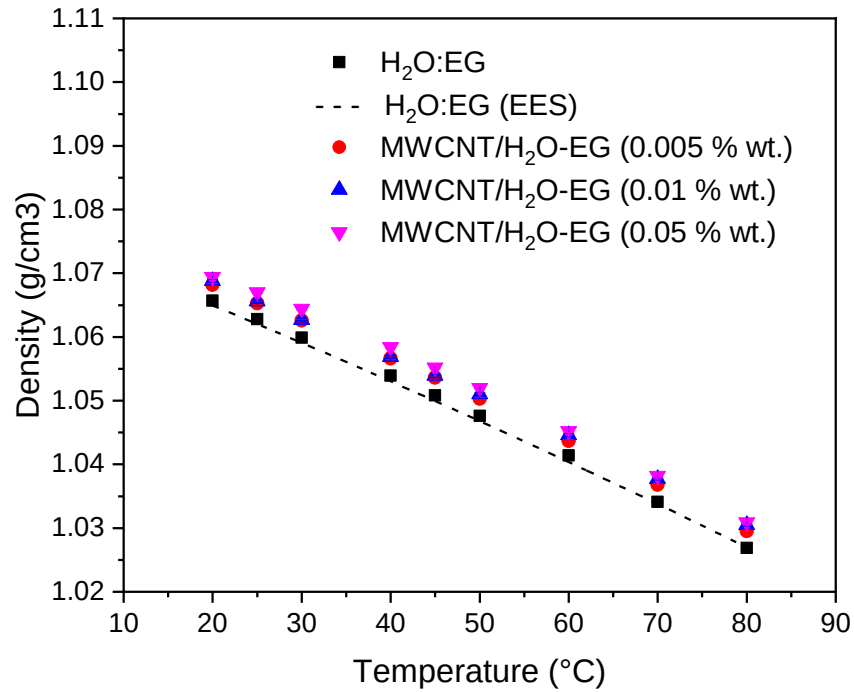
Fig. (4.8a - 4.8d) present the density results for all samples analyzed as they vary with temperature. The increments in density relative to the base fluid are as follows:

- For MWCNT nanofluids, the increments were 0.25 %, 0.31 % and 0.39 % for nanoparticle concentrations of 0.005 %, 0.01 % and 0.05 % respectively.
- For FMWCNT nanofluids, the increments were 0.37 %, 0.47 % and 0.55 % for nanoparticle concentrations of 0.005 %, 0.01 % and 0.05 % respectively.
- For graphene nanofluids, the density increments averaged 0.09 % and 0.19 % for nanoparticle concentrations of 0.005 % and 0.01 %, respectively.
- For industrial graphene nanofluids, the density increments averaged 0.4 % and 0.49 % for nanoparticle concentrations of 0.005 % and 0.01 %, respectively.

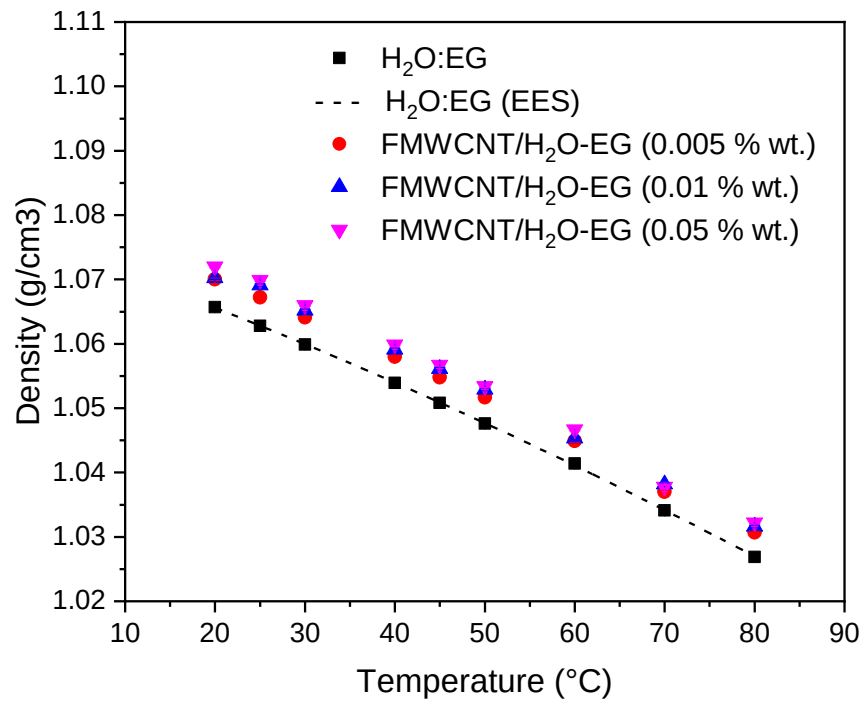
Fig. (4.8a) shows that the MWCNT/H₂O nanofluids presented a modest density increase of up to 0.39 %. According to (NABATI SHOGLI et al., 2016), for nanofluids based on MWCNT, density increased with an increase in concentration and decreased with an increase in temperature. On the other hand, the FMWCNT/H₂O - EG nanofluids shown in Fig. (4.8b) showed a more significant density increase of up to 0.55 %, probably due to the functionalization of the MWCNTs, which improves the dispersion of the nanoparticles and the interaction with the fluid, leading to a more homogeneous dispersion and stronger van der Waals forces between the nanoparticles and the fluid molecules, as highlighted by (ANGAYARKANNI and PHILIP, 2022). This stronger interaction is believed to be responsible for the greater increase in density observed in FMWCNT/H₂O - EG nanofluids compared to the non-functionalized counterparts.

Graphene nanofluids exhibited the least significant increase in density among the samples tested, as can be seen in Fig. (4.8c). The lower impact on density can be attributed to graphene's relatively lower mass density and the two-dimensional structure of graphene flakes, which may not contribute as significantly to the overall mass of the fluid as MWCNT. According to (ELSAID et al., 2021) the two-dimensional structure and relatively low mass density of

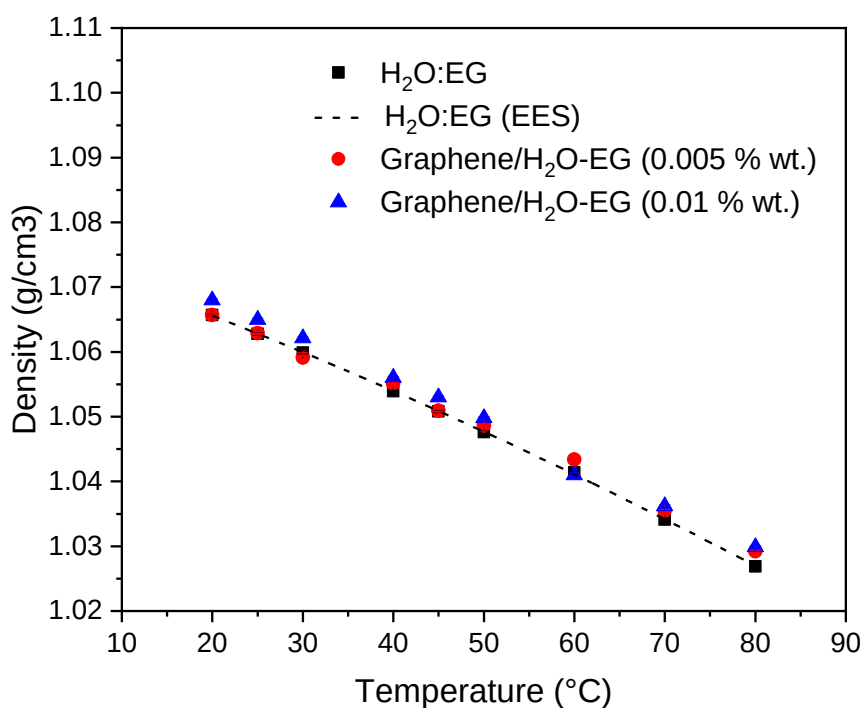
graphene result in minimal contributions to the overall mass of the nanofluid. Industrial graphene sample showed in Fig. (4.8d) presented moderate density increases, with increments up to 0.49 %.



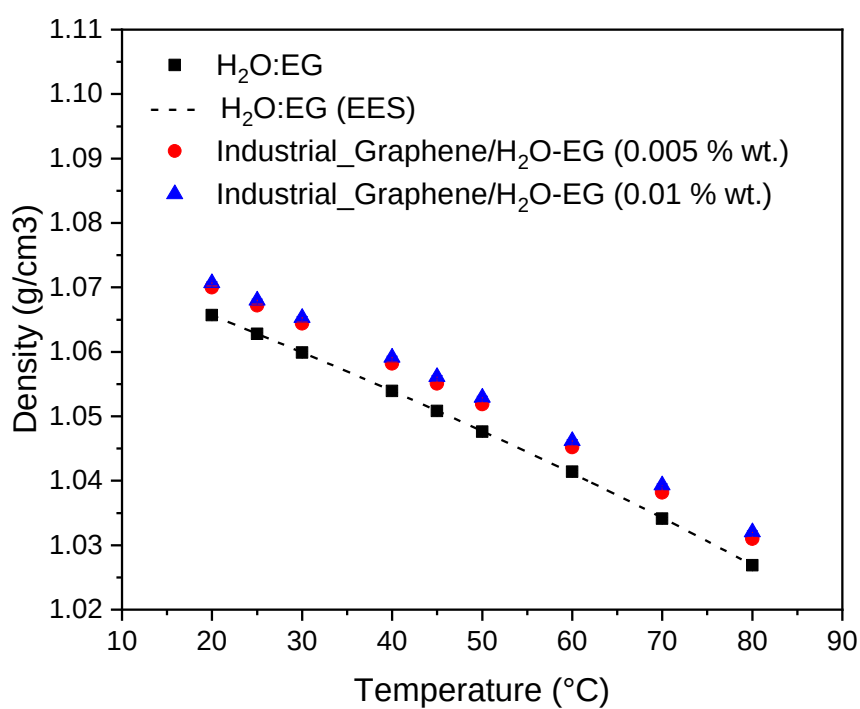
(a)



(b)



(c)



(d)

Figure 4.8 – Experimental for density of nanofluid samples and base fluid. (a) MWCNT/H₂O:EG. (b) FMWCNT/H₂O:EG. (c) Graphene/H₂O:EG. (d) Industrial graphene/H₂O:EG. Author's own.

The experimental results for the density suggested that the addition of nanoparticles, including MWCNTs, FMWCNTs, graphene, and industrial graphene, leads to an increase in the density of the base fluid, with the degree of enhancement varying according to the type and concentration of nanoparticles. Functionalized MWCNTs presented the most significant density increments, likely due to enhanced nanoparticle - fluid interactions. Conversely, graphene-based nanofluids exhibited the least density enhancement, suggesting that their primary benefits may be in other thermophysical properties, such as thermal conductivity. These findings highlight the necessity of selecting the appropriate nanoparticle types and concentrations to optimize nanofluid properties for specific applications.

4.2.4 Specific heat

The specific heat was determined assuming thermal equilibrium between the nanoparticles and the base fluid, using the classical model proposed by (XUAN and ROETZEL, 2000) described in Eq. (3.4). The model utilized the nanofluid density values shown in Fig. (4.8), the specific heat of nanoparticles as provided by the manufacturers, and the specific heat of the base fluid obtained from the EES (Engineering Equation Solver) software library. The results of the specific heat calculations for carbon nanotubes nanofluids and graphene nanofluids are showing in Fig. (4.9).

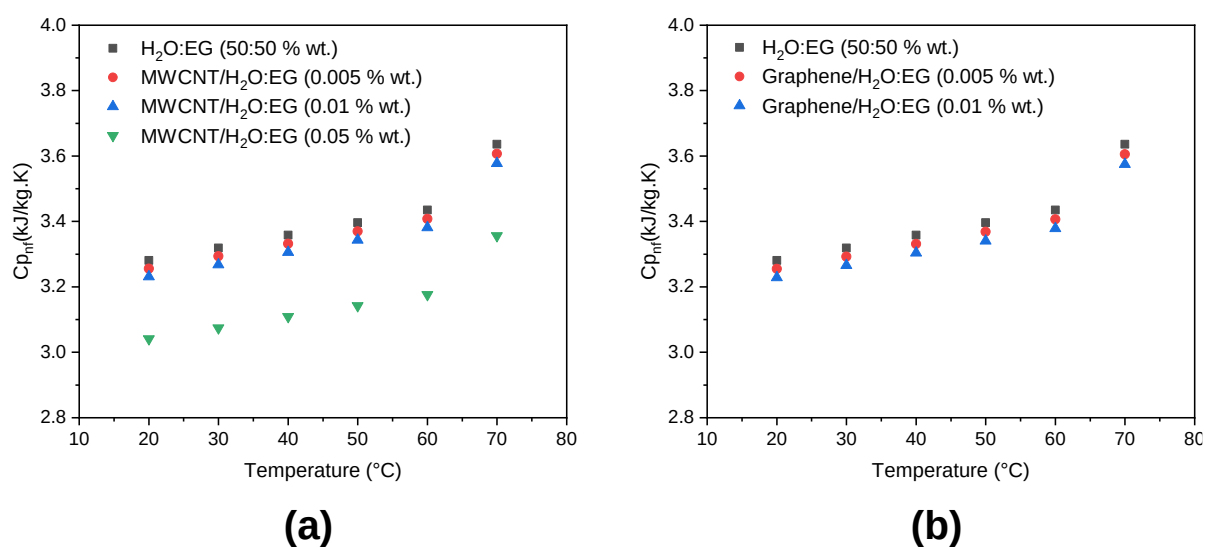


Figure 4.9 – Specific heat with different nanoparticles fractions in base fluid for: (a) MWCNT/H₂O-EG. (b) Graphene/H₂O-EG.

The specific heat behavior of nanofluids containing MWCNT and graphene dispersed in a water and ethylene glycol mixture, as shown in Fig. (4.9a) and Fig. (4.9b), reveals distinct trends influenced by nanoparticle concentration and type. Fig. (4.9a) show that the specific heat decreases with increasing MWCNT concentration. According to (OLIVEIRA *et al.*, 2023), as the concentration of MWCNTs increases, the overall specific heat capacity of the nanofluid decreases due to the higher thermal conductivity, resulting in a lower specific heat capacity of the nanotubes compared to the base fluid. The results also show that this effect becomes more pronounced at higher MWCNT concentrations, with the nanofluid containing 0.05 % wt. MWCNTs exhibiting the lowest specific heat among the samples tested.

For graphene nanofluids (Fig. 4.9b) the results indicated that the specific heat also decreases with increasing graphene concentration, though the effect is less pronounced than that observed with MWCNTs. This observation is supported by (ALHAKEEM, 2022), who noted that while graphene enhances thermal conductivity, its contribution to reducing specific heat is relatively modest due to its unique two-dimensional structure, which allows for better retention of thermal energy compared to one-dimensional nanotubes. The nanofluid containing 0.01 % wt. graphene shows a slight reduction in specific heat compared to the base fluid, highlighting the potential for graphene to improve thermal performance without significantly compromising the fluid's ability to store heat.

Overall, the analysis of specific heat in MWCNT and graphene nanofluids suggests that while both types of nanoparticles reduce the specific heat capacity of the base fluid, the extent of this reduction is dependent on the nanoparticle type and concentration. The findings underscore the importance of balancing thermal conductivity and specific heat in designing nanofluids for applications requiring both efficient heat transfer and thermal energy storage.

4.3 Heat transfer performance

After validation of experimental setup, it was possible to conduct the experimental tests and acquire the necessary data to evaluate the heat transfer coefficient and the pressure drop, which are essential parameters for assessing the thermohydraulic performance of the nanofluid samples based on the base fluid (H₂O-EG 50:50 % wt.). The experiments conducted for each geometry followed the conditions in Table 3.6. For nanofluids based on (H₂O-EG 50:50 % wt.) flowing through a straight pipe, 36 experiments were conducted per sample, totaling 288 experiments. For sudden contraction flows, 84 experiments per nanofluid were performed in

each of two geometries (CR = 1.4 and CR = 1.9), totaling 504 experiments for each geometry. For sudden expansion (ER = 1.7), 72 experiments per nanofluid were conducted, totaling 432 experiments. Each subsection will present the operational conditions for each investigated geometry, as well as the nanofluid samples used.

4.3.1 Convective heat transfer for straight pipe case

Table 4.1 present the operational conditions for each investigated nanofluid samples used in the straight pipe case in relation to the base fluid for the three different heat conditions investigated: 5 kW/m², 10 kW/m² and 12 kW/m². Three nanoparticles were employed: MWCNT, FMWCNT and graphene, all suspended in a mixture of water ethylene glycol 50:50 % in weight (H₂O-EG 50:50 % wt.).

Table 4.1 – Operational parameters for tests in the straight pipe.

Nanofluid	Mass fraction (φ wt.%)	Geometry	$\dot{m}$ (kg/s)	Reynolds	T _{inlet}	q" (W/m ²)
MWCNT/H ₂ O-EG 50:50 % wt.	0.005	Straight pipe	0.0157	500.4	25 °C	5000 10000 12000
FMWCNT/H ₂ O-EG 50:50 % wt.	0.01		0.0394	2500.2		
	0.05		0.1574	5000.4		
Graphene/H ₂ O-EG 50:50 % wt.	0.005		0.0093	538.4	45 °C	
	0.01		0.0787	2693		
			0.0933	5386		

Source: Author's own.

Figs. (4.10a), (4.11a) and (4.12 a) present the experimental data for convective heat transfer for the MWCNT, FMWCNT, and graphene nanofluid samples in the test section as a function of the mass flow rate ($\dot{m}[g/s]$) with a constant heat flux of 10 kW/m² and an inlet temperature of 25 °C. The analyzed experimental data show that in the laminar regime, the first two points in the graph, the nanofluids presented modest increments in heat transfer compared to the base fluid, especially for the most concentrated samples in the case of carbon nanotubes: ~ 8.44 % for MWCNT, ~ 18.03 % for FMWCNT. In the turbulent regime the increments were

a little bit more pronounced in the nanofluid samples at higher concentration: $\sim 12.2\%$ for MWCNT, $\sim 19.97\%$ for FMWCNT. For graphene, the most concentrated sample presented the best increments in heat transfer compared to base fluid: $\sim 18.15\%$.

Figs. (4.10b), (4.11b) and (4.12b) present the Nusselt number of MWCNT, FMWCNT, and graphene in the test section as a function of the Reynolds number Re for the laminar and turbulent regime, respectively. For the MWCNT in the less concentrated sample, there was a decrease in the Nusselt number of $\sim 1.17\%$ and a maximum increase for the Nusselt number of $\sim 4.88\%$ for the most concentrated sample. For nanofluids samples of FMWCNT and graphene, the Nusselt number was lower for the less concentrated samples: $\sim 13.15\%$ for FMWCNT and $\sim 5.06\%$ for graphene, therefore in the higher concentration samples were the best increments for Nusselt number: $\sim 13.97\%$ for FMWCNT and $\sim 14.48\%$ graphene.

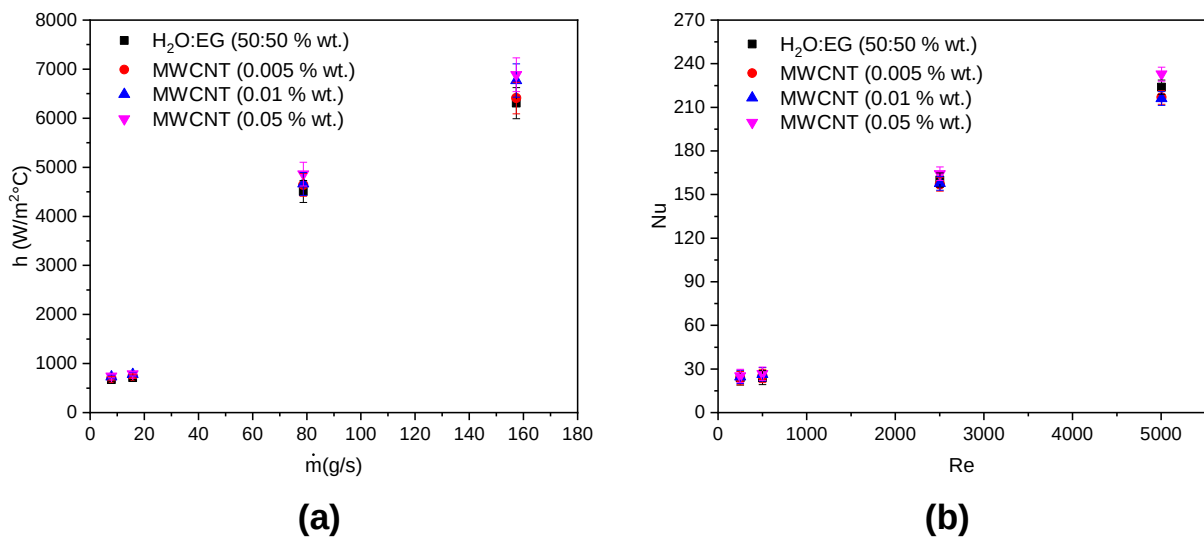


Figure 4.10 – Convective heat transfer and Nusselt number MWCNT nanofluid samples. (a) MWCNT ($h \times \dot{m}$). (b) MWCNT ($Nu \times Re$). Source: Author's own.

The maximum increments for h_{avg} was observed at a heat flux of 10 kW/m^2 , where the temperature distribution alongside the test section exceeded that of $q'' = 5 \text{ kW/m}^2$ and $q'' = 12 \text{ kW/m}^2$ conditions. In this sense when nanofluids were used at high temperatures, the density and viscosity differences between nanoparticles and the base fluid may produce an irregular flow behavior in nanofluids (CARDENAS CONTRERAS and BANDARRA FILHO, 2022). (TENG and YU, 2013) reported that the resistance of the thermal layer between nanoparticles and the base fluid intensifies due to these density differences, reducing the heat exchange capacity. Therefore, the probability of agglomeration increases due to the high aspect ratio of

MWCNTs, limiting the contact area and free movement of nanoparticles. Despite the Nusselt number increases with the increasing Reynolds number and mass concentration of nanofluid, in some cases the Nusselt number of the nanofluids analyzed suffers a decrease in relation to the base fluid. As previously mentioned, the irregular and random movements of nanoparticles affect the energy exchange rate in the base fluid exerting shear stress on the walls of the test section influencing the thermal dispersion of the flow. **APPENDIX H** shows the overall heat transfer enhancement for all samples analyzed in straight pipe case.

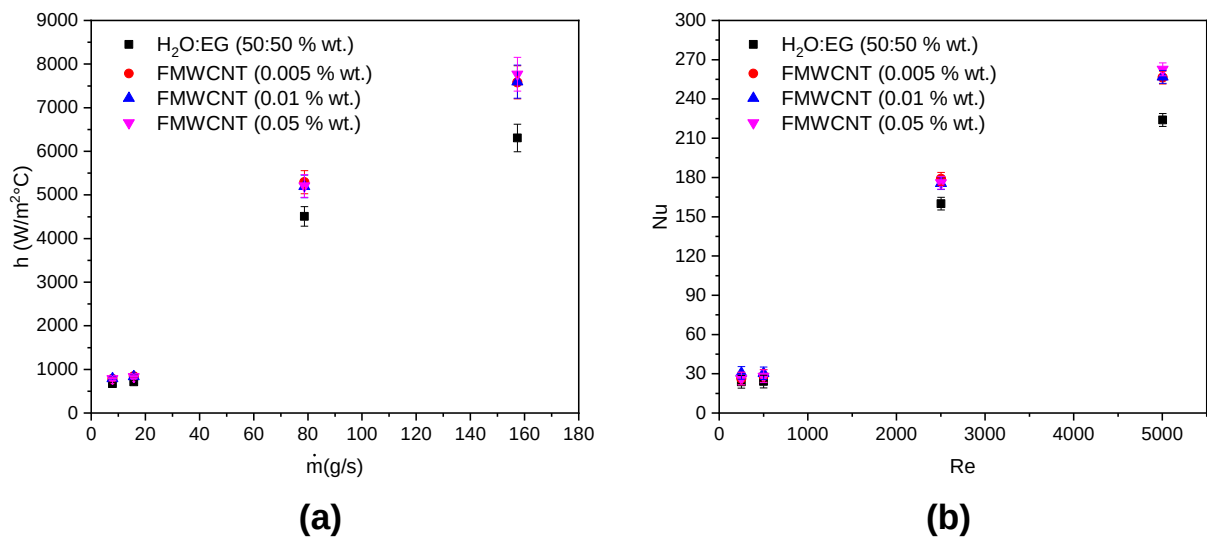


Figure 4.11 – Convective heat transfer and Nusselt number of FMWCNT nanofluid samples. (a) FMWCNT ($h \times \dot{m}$). (b) FMWCNT ($Nu \times Re$). Source: Author's own.

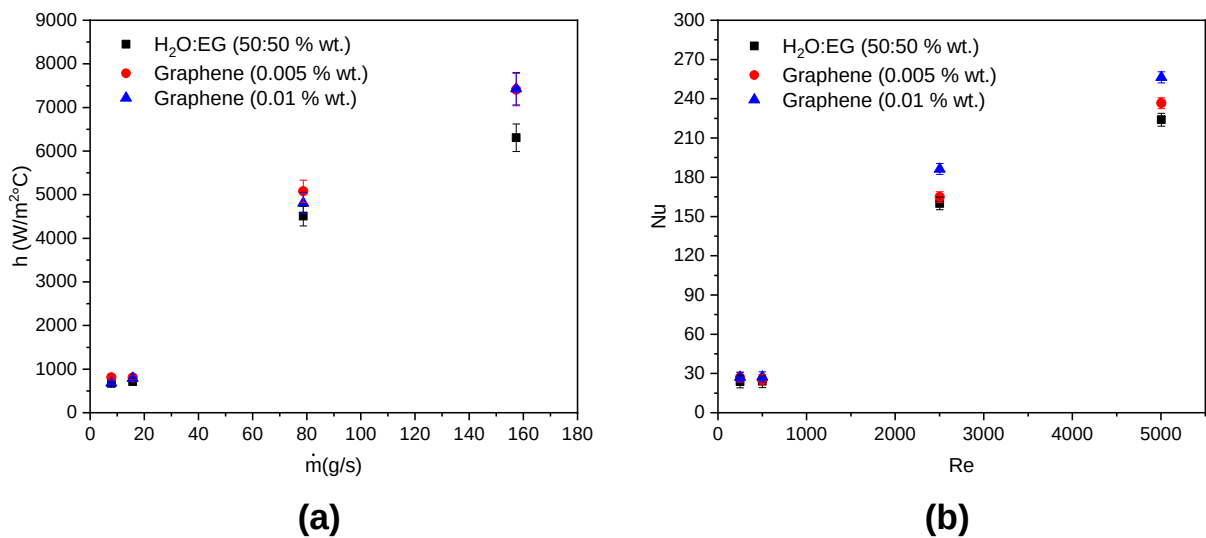


Figure 4.12 – Convective heat transfer and Nusselt number of graphene nanofluid samples. (a) Graphene ($h \times \dot{m}$). (b) Graphene ($Nu \times Re$). Source: Author's own.

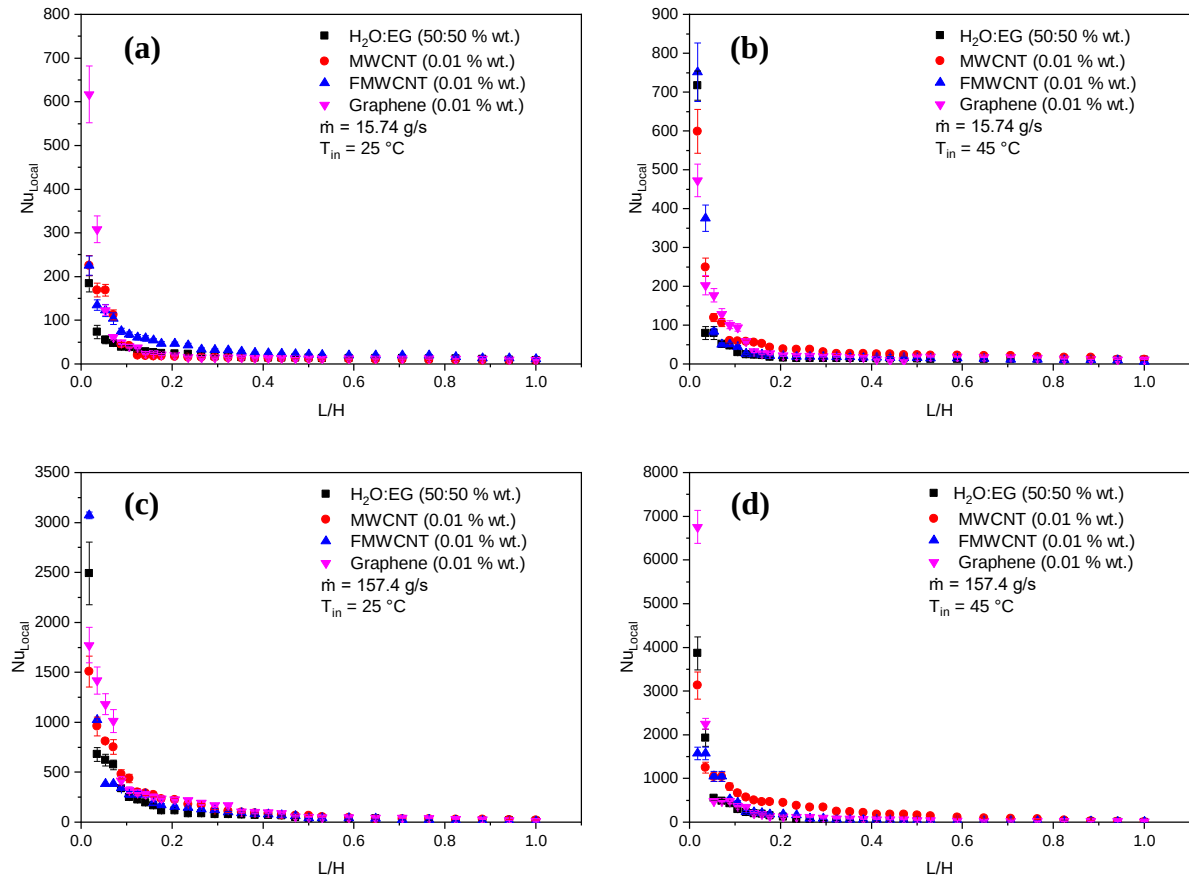


Figure 4.13 – Local Nusselt number for the nanofluids samples along the test section. (a) $\dot{m} = 15.74 \text{ g/s}$ and $T_{in} = 25 \text{ }^{\circ}\text{C}$. (b) $\dot{m} = 15.74 \text{ g/s}$ and $T_{in} = 45 \text{ }^{\circ}\text{C}$. (c) $\dot{m} = 157.4 \text{ g/s}$ and $T_{in} = 25 \text{ }^{\circ}\text{C}$. (d) $\dot{m} = 157.4 \text{ g/s}$ and $T_{in} = 45 \text{ }^{\circ}\text{C}$. Source: Author's own.

All nanofluids samples were performed for a range of mass flow rate ($\dot{m}$) between 15.74 g/s and 157.4 g/s, the heat flux applied varying between 5 kW/m² to 12 kW/m². Two inlet temperatures were employed, $T_{in} = 25 \text{ }^{\circ}\text{C}$ and $T_{in} = 45 \text{ }^{\circ}\text{C}$ and the nanofluids flowing in a range of Reynolds Number between approximately 500 and 5400. Figs. 4.13 (a-d) shows the influence of the flow regime (laminar or turbulent) and the inlet temperature of the nanofluid into the test section on the local Nusselt number along the pipe with a constant heat flux of 10 kW/m². At the inlet temperature of 25 °C in the laminar and turbulent regime, the FMWCNT and graphene nanofluid samples lead to the highest values of local Nusselt number since they have higher values for convective heat transfer compared to MWCNT nanofluid samples. This is due to the slightly higher thermal conductivity values of FMWCNT and graphene samples than MWCNT samples. The local Nusselt number values for MWCNT and FWCNT nanofluid samples are slightly higher compared to those for graphene nanofluid samples. This is due to the higher thermal conductivity of graphene nanofluids in comparison to carbon nanotubes at

higher temperatures. It is important to highlight that at high temperatures, nanofluids can degrade, leading to reduced heat transfer efficiency and impaired thermal performance. This degradation, which varies among different nanofluids, may result from nanoparticle agglomeration, sedimentation, or chemical instability. Such issues can decrease thermal conductivity and increase viscosity, ultimately lowering the heat transfer efficiency of the system and impairing its overall thermal performance. Also, the variation in the Nusselt number near the inlet compared to further downstream is primarily attributed to the developing thermal boundary layer, the temperature-dependent properties of the nanofluid, potential flow regime transitions, entrance effects, and the interaction with constant heat flux. These factors, influenced by the inlet temperature, result in distinct heat transfer behaviors along the pipe's length (HILO et al., 2020; KIA et al., 2023; SAJID and ALI, 2019; SELIMEFENDIGIL et al., 2019).

4.3.2 Convective heat transfer for nanofluid flowing under contraction

Table 4.2 present the operational conditions for each investigated nanofluid samples used for the nanofluid flowing under contraction. The presence of a sudden contraction induces a pressure drop due to the abrupt increase in velocity and the consequent energy loss attributed to turbulence. Turbulence regions manifest both upstream and downstream of the contraction. A reduction in the contraction ratio precipitates a sharp alteration in the velocity gradient. According to (SONG *et al.*, 2023), flow separation divides the flow field within the annular gap into distinct zones, including the recirculation zone, shear layer, and main region. The flow within the shear layer is significantly influenced by boundary conditions, draining into both the recirculation zone and the main current region.

Fig. (4.14a) and Fig. (4.15a) display the experimental results for heat transfer as a function of mass flow rate for MWCNT nanofluids following sudden contraction in the laminar flow, for cases with contraction ratios (CR) of 1.4 and 1.9, respectively.

The results suggested a considerable enhancement in heat transfer for samples with higher nanoparticle concentrations: 6.88 % for a contraction ratio of 1.4 and 6.43 % for a contraction ratio of 1.9, both with MWCNT nanofluids at a mass fraction of 0.01 % wt. This indicates that the combined effect of nanoparticle mass fraction in the sample, along with the presence of recirculation zones, contributes to enhanced thermal performance. According to (ALSABERY *et al.*, 2021), in horizontal channels, recirculation is relatively less intense near the bottom wall compared to the top, where convective heat transfer plays a significant role.

Table 4.2 – Operational parameters for tests of nanofluid flowing under contraction.

Nanofluid	Mass fraction (ϕ wt.%)	Geometry	$\dot{m}$ (kg/s)	Reynolds	T_{inlet}	q'' (W/m ²)
MWCNT/H ₂ O-EG 50:50 % wt.	0.005	CR = 1.4	0.0157	500.4	25 °C	5000
			0.0236	750.6		
			0.0315	1001		
			0.0394	1251		
			0.0787	2502		
			0.1102	3503		
			0.1574	5004	45 °C	10000
			0.0093	538.4		
			0.0140	807.9		
			0.0187	1077		
Graphene/H ₂ O-EG 50:50 % wt.	0.01	CR = 1.9	0.0233	1346		12000
			0.0467	2693		
			0.0653	3771		
			0.0933	5386		

Source: Author's own.

Fig. (4.14b) and Fig. (4.15b) illustrate the findings for the Nusselt number of MWCNT nanofluids flowing in the turbulent regime within the test section following sudden contraction for the analyzed cases.

The results demonstrate a consistent trend of increased heat transfer with higher mass fractions and Reynolds numbers. Moreover, the increase in contraction ratio leads to a rise in the heat transfer coefficient, enhancing the mixture due to the generation of recirculation zones. As the nanofluid temperature increases along the test section, the viscous effects diminish, resulting in a reduced requirement for additional pumping power and an increase in the Reynolds number, which impacts the heat transfer phenomena.

The maximum increments of the Nusselt number obtained for MWCNT nanofluid samples relative to the base fluid were 2.7 % for a contraction ratio of 1.4 and 3.37 % for a contraction ratio of 1.9. According to (YANG *et al.*, 2021), in the vicinity of the region with geometry change, turbulence intensifies, and nanoparticles vigorously collide with the wall surface, resulting in enhanced heat transfer effects. With an increasing Reynolds number, the disruption, separation, and shear phenomena become more pronounced, leading to increased heat removal.

It is noteworthy that the increase in the contraction ratio leads to a rise in the heat transfer coefficient. This phenomenon can be attributed to the generation of recirculation zones occurring both before and after the nanofluid flow following sudden contraction in a closed conduit, as observed in studies by (ABDULRAZZAQ *et al.*, 2020d, 2020b; TOGUN *et al.*, 2014a).

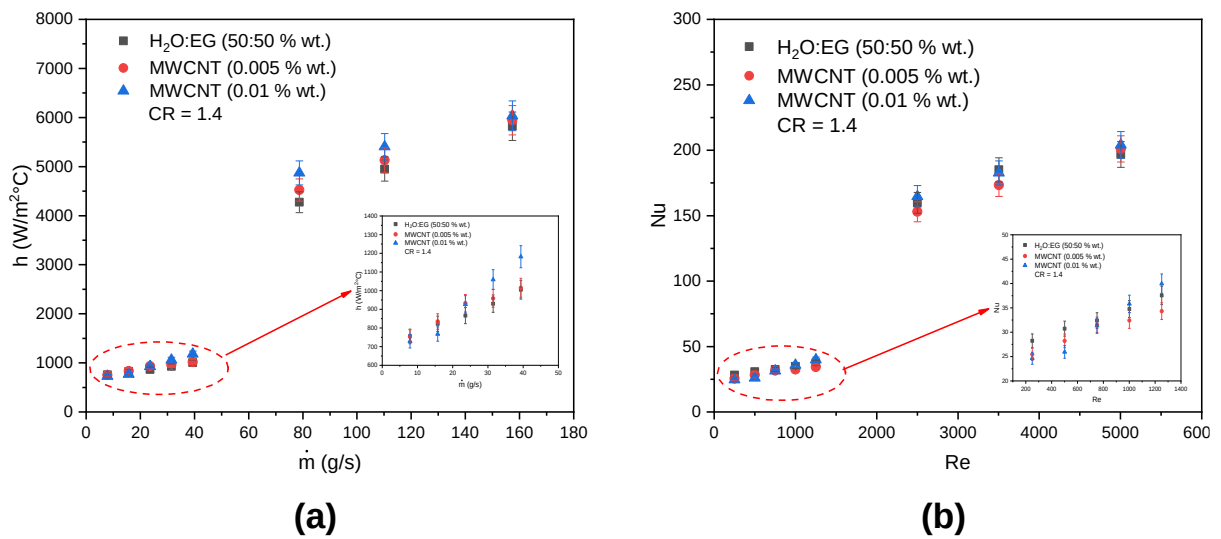


Figure 4.14 – Convective heat transfer and Nusselt number MWCNT nanofluid samples with $T_{in} = 25$ °C and $q'' = 10$ kW/m² for: (a) MWCNT ($h \times \dot{m}$) and CR = 1.4; (b) MWCNT ($Nu \times Re$) and CR = 1.4. Source Author's own.

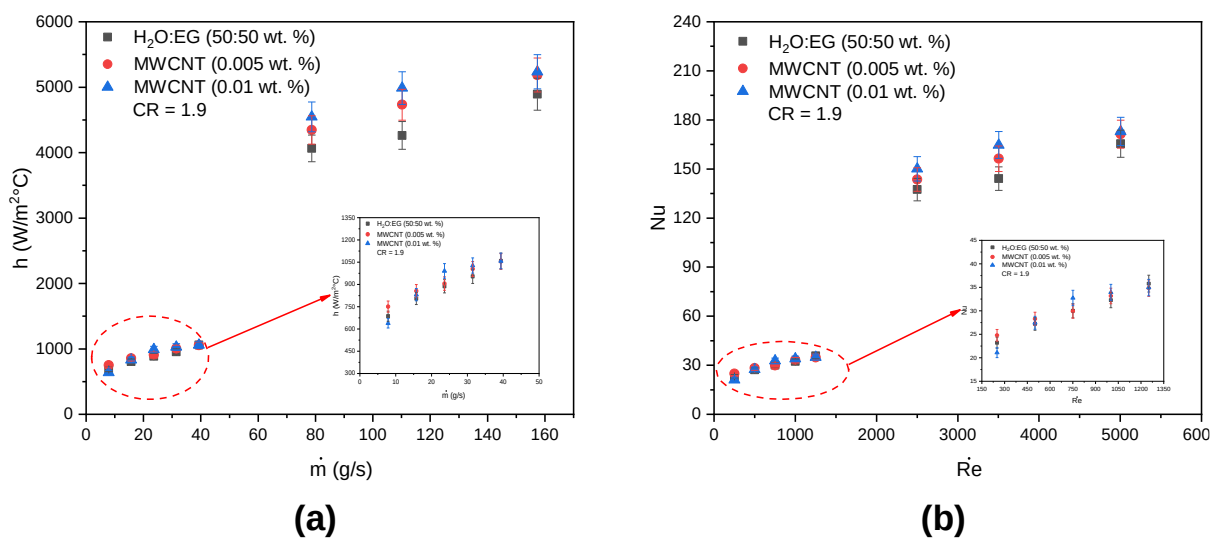


Figure 4.15 – Convective heat transfer and Nusselt number MWCNT nanofluid samples with $T_{in} = 25$ °C and $q'' = 10$ kW/m² for: (a) MWCNT ($h \times \dot{m}$) and CR = 1.4; (b) MWCNT ($Nu \times Re$) and CR = 1.4. Source Author's own.

Fig. (4.16) and Fig (4.17) shown some finds for convective heat transfer as a function of mass flow rate for FMWCNT nanofluids. The utilization of oleic acid as a functionalizing agent in MWCNT for superficial modification enhances the stability of nanofluid samples, particularly at lower concentrations. At elevated temperatures, the reduction in viscous effects necessitates less pumping power increment and increases the Reynolds Number, thereby impacting the heat transfer phenomena. Additionally, the increase in the contraction ratio results in an enhancement of the heat transfer coefficient due to the generation of recirculation zones (BASHIR et al., 2019; KAZI and TOGUN, 2015; TOGUN et al., 2013b).

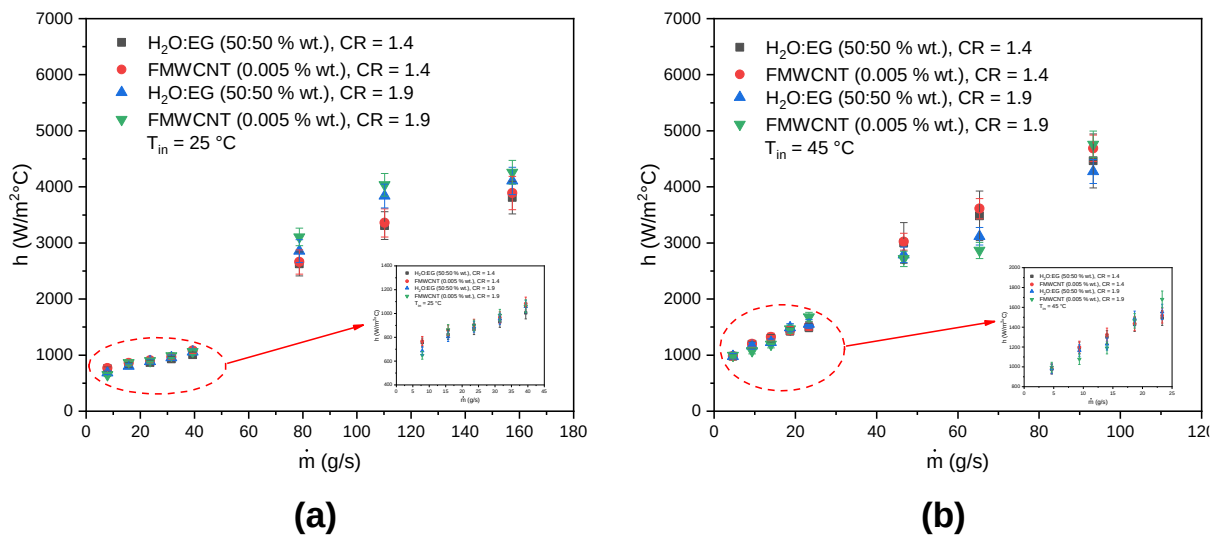


Figure 4.16 – Convective heat transfer for FMWCNT nanofluid samples at different contraction ratios. (a) $T_{in} = 25$ °C and 0.005 % wt. (b) $T_{in} = 45$ °C and 0.005 % wt. Source: Author's own.

The maximum increment for FMWCNT nanofluid flowing at contraction ratio of 1.4 (CR = 1.4) noticed was approximately 11 % for the sample with 0.01 % wt. in relation to the base fluid at inlet temperature of 25 °C. For inlet temperature of 45 °C the maximum increment observed was around 6 % for FMWCNT sample with 0.01 % wt. in relation to the base fluid.

For the case of CR = 1.9, the FMWCNT nanofluid showed a more significant enhancement. The maximum observed increase was about 22 % for the 0.01 % wt. sample at an inlet temperature of 25°C. However, at an inlet temperature of 45 °C, the increase was lower, approximately 4 %, again compared to the base fluid.

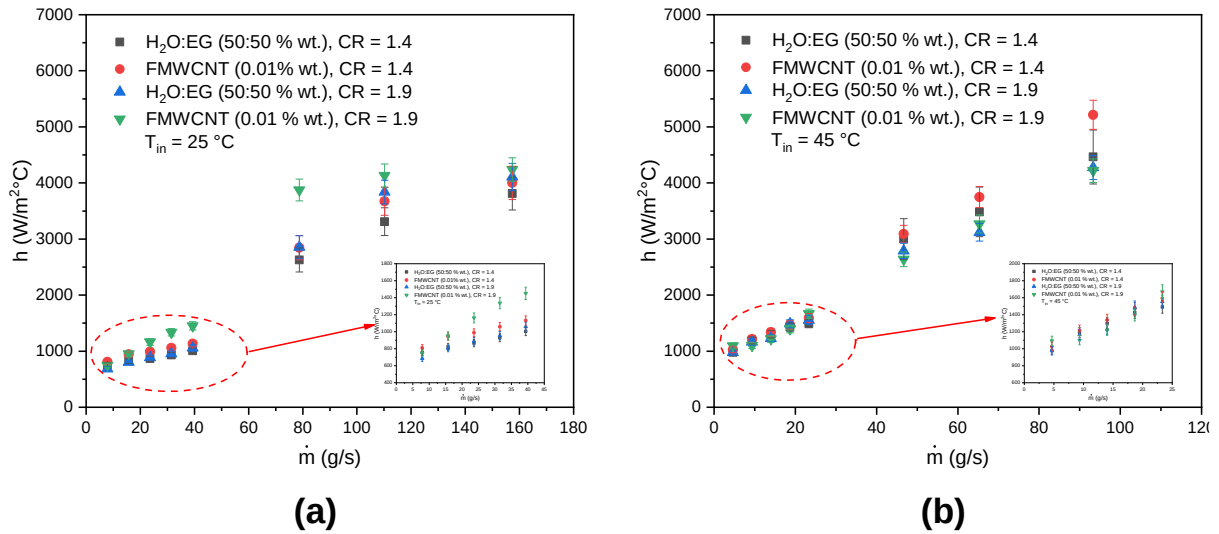


Figure 4.17 – Convective heat transfer for FMWCNT nanofluid samples at different contraction ratios. (a) $T_{in} = 25\text{ °C}$ and 0.01 % wt. (b) $T_{in} = 45\text{ °C}$ and 0.01 % wt. Source: Author's own.

The data obtained of Fig (4.16) and Fig. (4.17) suggested that at an inlet temperature of 25 °C , the heat transfer coefficient increases with the mass flow rate for both contraction ratios. Notably, the higher contraction ratio ($CR = 1.9$) significantly enhances the heat transfer coefficient compared to $CR = 1.4$, indicating that a larger contraction ratio promotes more efficient heat transfer. At the elevated inlet temperature of 45 °C , the overall heat transfer coefficients are slightly lower, suggesting that while higher temperatures reduce nanofluid viscosity and improve flow conditions, the corresponding enhancement in heat transfer is less pronounced. According (ABDULRAZZAQ *et al.*, 2020b) the formation of recirculation zones due to the higher contraction rates contributes significantly to the improvements observed in convective heat transfer. **APPENDIX I** and **APPENDIX J** show the overall heat transfer enhancements for the case of $CR = 1.4$ and $CR = 1.9$ respectively.

Fig. (4.18a) and (4.18b) illustrate the local Nusselt number for graphene nanofluids with mass fractions of 0.005 % wt. and 0.01 % wt. along the axial position for laminar and turbulent regimes respectively. The Nusselt number demonstrates an increase with both the mass fraction and the Reynolds Number. At the entrance, the local Nusselt number experiences a sudden increase until the reattachment point of the flow, attributed to the turbulence region at the flow inlet. After the reattachment point, the Nusselt number decreases and tends to equalize at $L/D = 0.4$, where the flow detaches. Subsequently, the local Nusselt number experiences a slight increase before decreasing abruptly and reaching a stable point along the second half of the test section.

Fig. (4.18c) and (4.18d) depict the relative Nusselt number (Nu_{nf}/Nu_{bf}) along the test section for the laminar and turbulent regimes respectively. For mass flow rates of $\dot{m} = 0.0157$ kg/s, at $L/D = 0.12$, $L/D = 0.24$, and $L/D = 0.32$, the maximum increments were 53 %, 82 %, and 46 % respectively for graphene samples with a mass fraction of 0.005 % wt., and 67 %, 63 %, and 53 % for graphene samples with a mass fraction of 0.01 % wt. at the same axial positions. The average relative Nusselt number for $\dot{m} = 0.0157$ kg/s was approximately 18 % for the graphene sample with 0.005 % wt., and 25 % for the graphene sample with 0.01 % wt.

For a mass flow rate of $\dot{m} = 0.157$ kg/s, at $L/D = 0.38$ and $L/D = 0.5$, the maximum increments in relative Nusselt number were 73 % and 54 % respectively for graphene samples with a mass fraction of 0.005 % wt., and 74 % and 79 % respectively for graphene samples with a mass fraction of 0.01% wt. at the same radial positions.

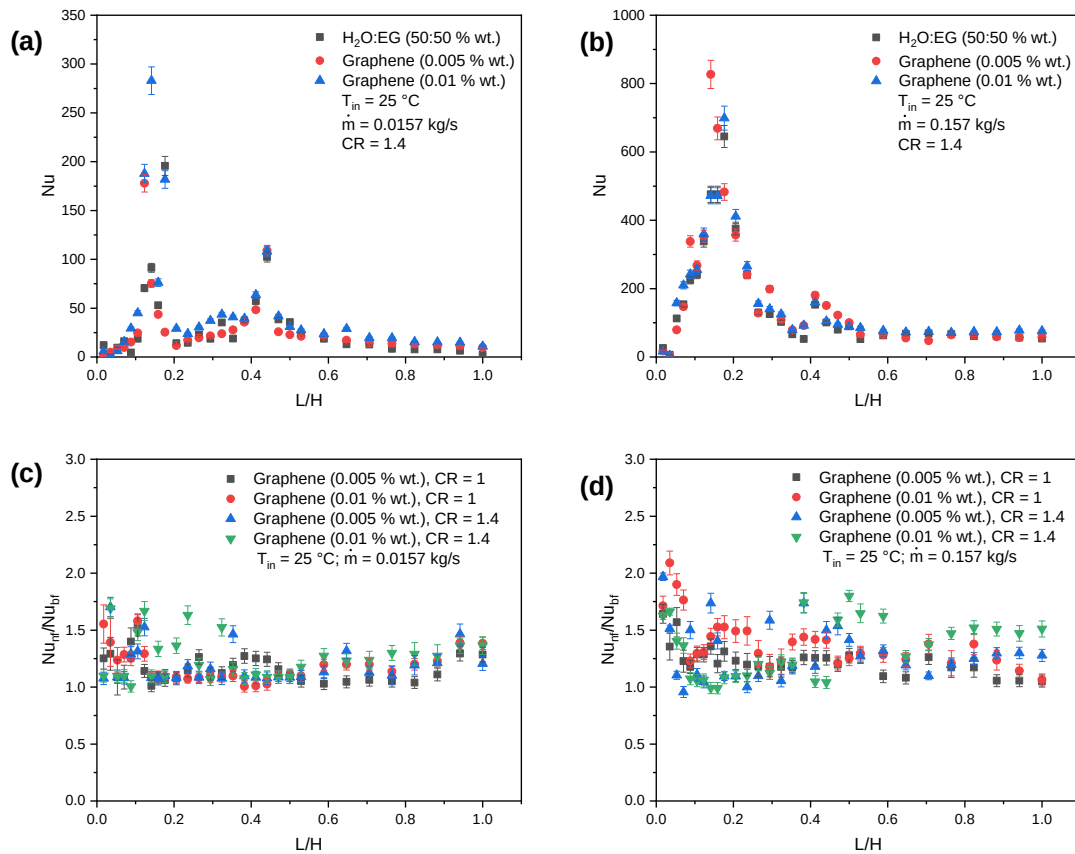


Figure 4.18 – Local Nusselt number along the axial position for: (a) $\dot{m} = 0.0157$ kg/s; (b) $\dot{m} = 0.157$ kg/s. Relative Nusselt number along the axial position for: (c) $\dot{m} = 0.0157$ kg/s; (d) $\dot{m} = 0.157$ kg/s. Source: Author's own.

4.3.3 Convective heat transfer for nanofluid flowing under expansion

Table 4.3 outlines the operational conditions for each nanofluid sample performed during flow expansion, compared to the base fluid, under three distinct heat conditions: 5 kW/m², 10 kW/m² and 12 kW/m². Three nanoparticles were employed: MWCNT, FMWCNT and Industrial graphene, all suspended in a mixture of water ethylene glycol 50:50 % in weight (H₂O-EG 50:50 % wt.).

Table 4.3 – Operational parameters for tests of nanofluid flowing under expansion.

Base fluid	Mass fraction (φ wt.%)	Geometry	$\dot{m}$ (kg/s)	Reynolds	T_{inlet}	q'' (W/m2)		
MWCNT/H ₂ O-EG 50:50 % wt.	0.005	ER = 1.7	0.0157	500.4	25 °C	5000		
			0.0236	750.6				
			0.0315	1001				
			0.0394	1251				
			0.0787	2502				
FMWCNT/H ₂ O-EG 50:50 % wt.			0.0093	538.4	45 °C		10000	
			0.0140	807.9			12000	
Industrial graphene/H ₂ O-EG 50:50 % wt.			0.0187	1077			45 °C	
			0.0233	1346				
			0.0467	2693				
	0.0653	3771						
	0.0933	5386						

Source: Author's own.

Figs. (4.19), (4.20) and (4.21) present the experimental data for the convective heat transfer for MWCNT, FMWCNT, and industrial graphene nanofluid samples in the test section as a function of the mass flow rate ($\dot{m}$ [g/s]) with a constant heat flux of 10 kW/m² and inlet temperature of 25 °C and 45 °C. According to the results the maximum heat transfer enhancement occurs at inlet temperature of 25 °C for all samples analyzed. For MWCNT, enhancements reached 12.49 % and 16.56 % at $\phi = 0.005\%$ and $\phi = 0.01\%$, respectively (Fig. 4.19a), while at 45 °C, the enhancements were 6.12 % and 8.14 % (Fig. 4.19b). FMWCNT showed enhancements of 8.95 % and 18.06 % at 25 °C (Fig. 4.20a), and 7.24 % and 5.65 % at 45 °C (Fig. 4.20b). For industrial graphene, the enhancements were 9.67 % and 11.98 % at 25 °C (Fig. 4.21a), and 4.19 % and 5.02 % at 45 °C (Fig. 4.21b).

Figs. (4.22), (4.23) and (4.24) present the Nusselt number of MWCNT, FMWCNT, and industrial graphene in the test section as a function of the Reynolds number Re with a constant heat flux of 10 kW/m^2 and inlet temperature of 25°C and 45°C . For the MWCNT nanofluid, the Nusselt number increased by approximately 2.03 % in the less concentrated sample and by up to 5.72 % in the most concentrated sample at 25°C . At 45°C , the Nusselt number decreased by about 1.28 % in the less concentrated sample and increased by up to 3 % in the most concentrated sample. For the FMWCNT nanofluid at 25°C , the Nusselt number decreased by around 1.18 % in the less concentrated sample and increased by up to 9.63 % in the most concentrated sample. At 45°C , it decreased by approximately 2.5 % and 1.72 % in the less and more concentrated samples, respectively. The industrial graphene nanofluid showed a decrease of about 0.53% in the less concentrated sample and an increase of up to 1.56 % in the most concentrated sample at 25°C . At 45°C , the Nusselt number decreased by around 5.27 % and 4.53 % in the less and more concentrated samples, respectively.

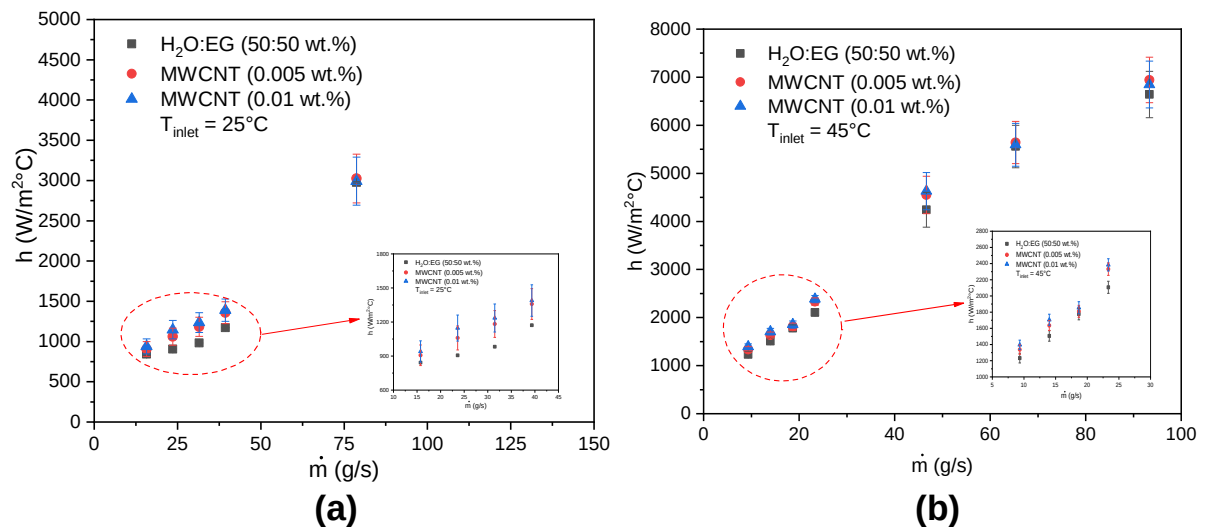


Figure 4.19 – Convective heat transfer for MWCNT nanofluid samples. (a) $T_{in} = 25^\circ\text{C}$ (b) $T_{in} = 45^\circ\text{C}$. Source: Author's own.

The convective heat transfer performance of MWCNT, FMWCNT, and industrial graphene nanofluids, as illustrated in Figs. (4.19) to (4.21), shows a significant enhancement at an inlet temperature of 25°C , particularly at higher nanoparticle concentrations. For example, MWCNT nanofluids exhibited an increase in the heat transfer coefficient by up to 16.56 % at a concentration of 0.01 % wt. and 25°C . According (APMANN et al., 2021; EANEST JEBASINGH and VALAN ARASU, 2020) lower temperatures enhance nanoparticle

dispersion and reduce agglomeration, leading to improved thermal conductivity and heat transfer efficiency. Functionalization of MWCNTs further improves these effects, as seen in the FMWCNT nanofluids, which displayed even higher enhancements, suggesting that functionalization enhances nanoparticle-fluid interactions, thereby optimizing heat transfer (LI et al., 2020).

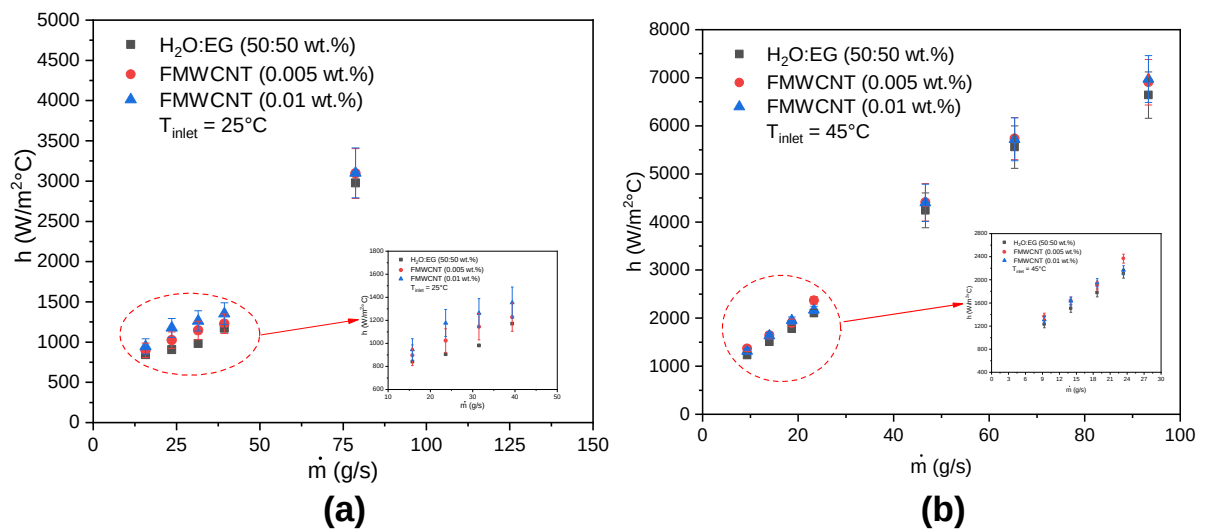


Figure 4.20 – Convective heat transfer for FMWCNT nanofluid samples. (a) $T_{in} = 25^\circ\text{C}$ (b) $T_{in} = 45^\circ\text{C}$. Source: Author's own.

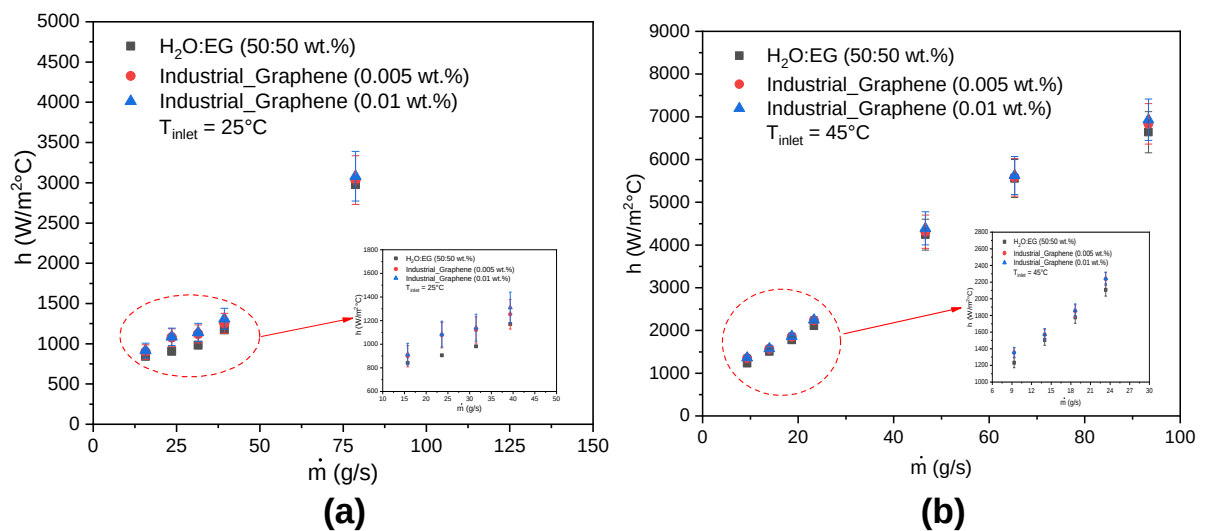


Figure 4.21 – Convective heat transfer for Industrial graphene nanofluid samples. (a) $T_{in} = 25^\circ\text{C}$ (b) $T_{in} = 45^\circ\text{C}$. Source: Author's own.

The Nusselt number trends, as shown in Figs. (4.22) to (4.24), support the observation that nanofluids are more effective at lower temperatures. For MWCNT nanofluids, the Nusselt number increased by 5.72 % at 25 °C and higher concentrations, but the increase was less pronounced at 45 °C, and in some cases, there was even a decline. These finds align with the results of (NOORZADEH *et al.*, 2020; ZHOU *et al.*, 2024) which indicate that thermal conductivity can plateau or decline at elevated temperatures due to factors such as increased viscosity and nanoparticle agglomeration. Additionally, the reduction in the effectiveness of nanofluids at higher temperatures could be due to diminished Brownian motion, which is a crucial mechanism for enhancing convective heat transfer (MOZAFARY *et al.*, 2024).

In the case of FMWCNT and industrial graphene nanofluids, similar trends were observed. The FMWCNT nanofluids, for instance, showed a notable Nusselt number increase of 9.63 % at 25 °C. However, at 45 °C, the Nusselt number generally decreased, reflecting a less effective heat transfer process. This reduction can be attributed to the decreased thickness of the thermal boundary layer at higher temperatures, which limits the enhancement effects of the nanoparticles (JALILI *et al.*, 2023). Furthermore, the surface area-to-volume ratio of graphene and MWCNT particles, which significantly contributes to the enhancement of heat transfer, appears to be less effective as the temperature increases, leading to the observed decline in performance (POZZI *et al.*, 2024).

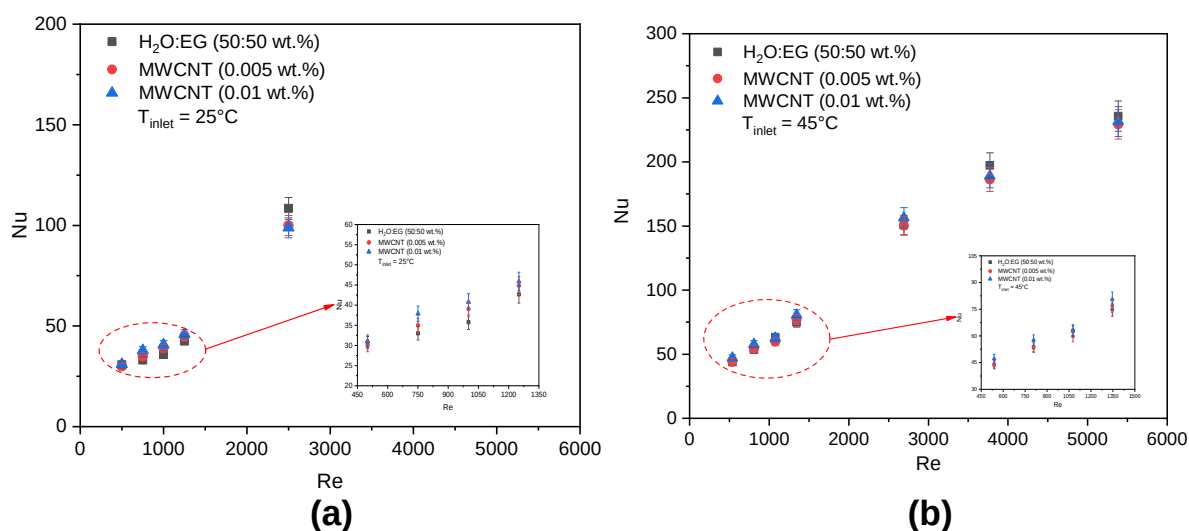


Figure 4.22 – Nusselt number for MWCNT nanofluid samples. (a) $T_{in} = 25\text{ }^{\circ}\text{C}$ (b) $T_{in} = 45\text{ }^{\circ}\text{C}$.

Source: Author's own.

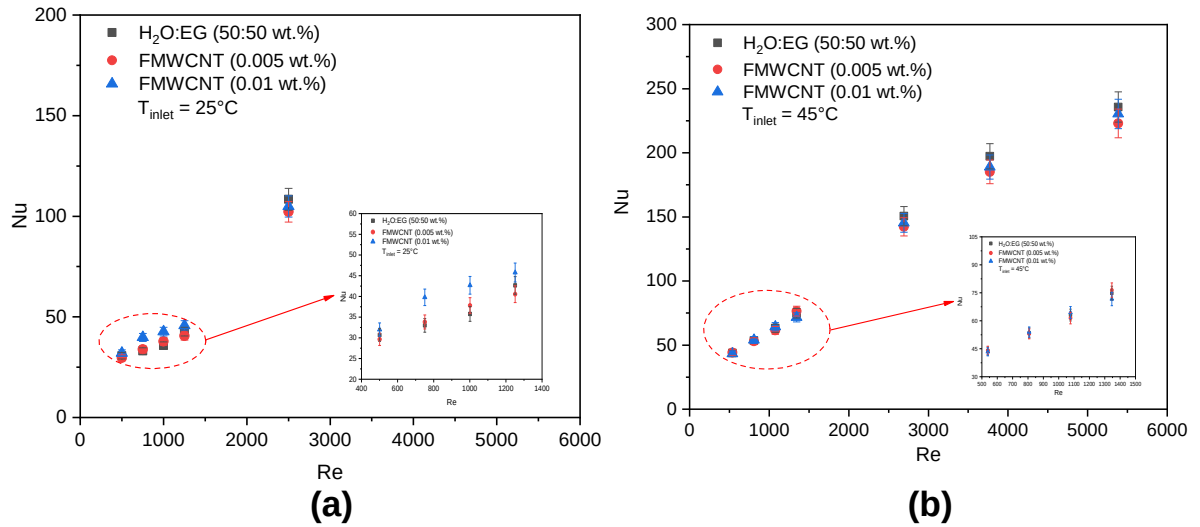


Figure 4.23 – Nusselt number for FMWCNT nanofluid samples. (a) $T_{in} = 25^\circ\text{C}$ (b) $T_{in} = 45^\circ\text{C}$.

Source: Author's own.

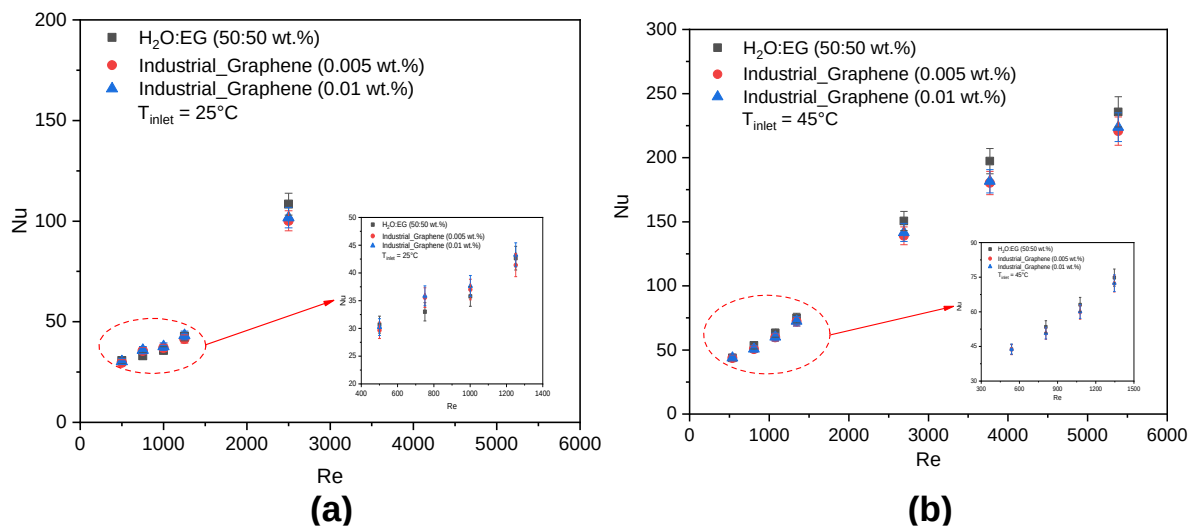


Figure 4.24 – Nusselt number for Industrial graphene nanofluid samples. (a) $T_{in} = 25^\circ\text{C}$ (b) $T_{in} = 45^\circ\text{C}$. Source: Author's own.

The results indicate that while nanofluids such as MWCNT and FMWCNT show substantial improvements in heat transfer at lower temperatures, their effectiveness diminishes at higher temperatures. This suggests the need for careful optimization of nanoparticle concentration, functionalization, and operating conditions to maximize thermal performance. These findings are supported by (EANEST JEBASINGH and VALAN ARASU, 2020; YANG et al., 2012), which emphasizes the critical role of maintaining stable nanoparticle dispersion

and minimizing agglomeration to sustain the enhanced thermal properties of nanofluids across varying temperatures. **APPENDIX K** show the overall heat transfer enhancements for the case of $ER = 1.7$.

4.4 Friction factor and pressure drop

4.4.1 Nanofluid flowing in a straight pipe

Figs (4.25a), (4.26a) and (4.27a) present the pressure drop for the nanofluid samples of MWCNT, FMWCNT, and graphene in the test section as a function of the mass flow rate, $\dot{m}[g/s]$. The experimental pressure drop results for all nanofluid samples analyzed showed that the turbulent regime did not present significant differences in pressure drop in the test section compared to the base fluid. In the laminar regime, however, the nanofluids showed substantial increments in pressure drop compared to the base fluid, especially for the highest concentrated samples: $\sim 31\%$ for MWCNT, $\sim 26.25\%$ for FMWCNT and $\sim 12.68\%$ for graphene. According (MINAKOV *et al.*, 2016), with increasing size of nanoparticles the pressure drop decreases due to lower viscosity.

Figs (4.25b), (4.26b) and (4.27b) show the friction factor for MWCNT, FMWCNT, and graphene nanofluid samples in the test section as a function of the Reynolds number Re , compared with the models described in the Eq. (3.10) and Eq. (3.11) for laminar and turbulent flow respectively. All samples showed a mean deviation of approximately 20% from the theoretical model for laminar results. In the turbulent regime, however the mean deviation of the experimental results and the theoretical model of Blasius was approximately 3% on average for all analyzed cases.

As previously mentioned, the pressure drop measurement was obtained by comparing the measurements of two pressure transmitters positioned at the inlet and outlet of the test section, and their readings were cross-checked with the values obtained by a differential transducer. The measurements necessary to determine the fluid dynamic behavior were obtained simultaneously with the thermal tests, and the experimental results for the friction factor were obtained employing the pressure drop in the test section according to Eq. (3.9). As can be seen, the results of the flow characteristics and the fluid dynamic behavior for base fluid and the nanofluid samples in the test section showed a reasonable agreement with models used to validate the experimental setup.

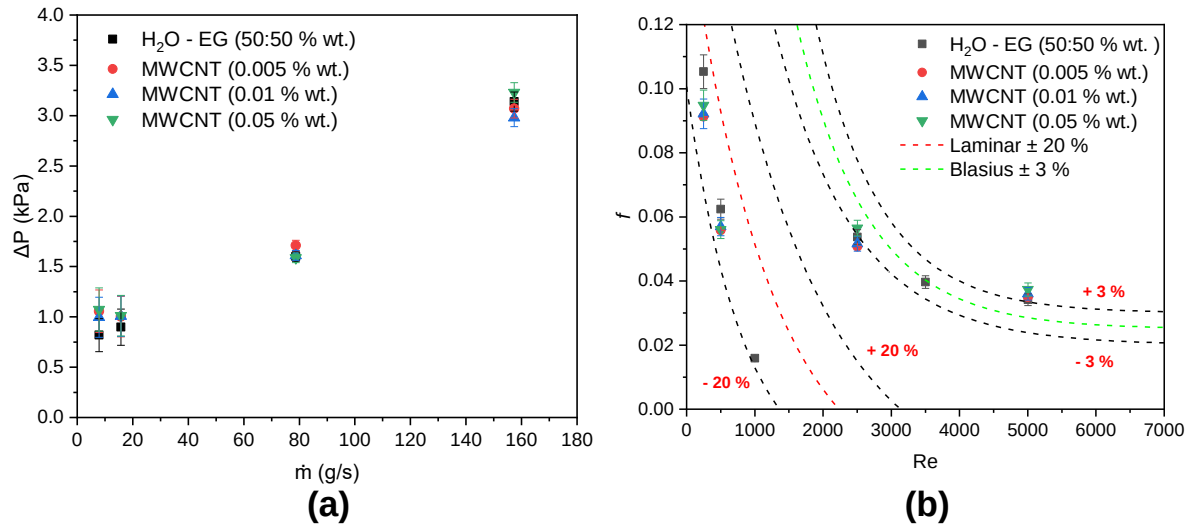


Figure 4.25 – Pressure loss and friction factor for MWCNT nanofluid samples. (a) MWCNT ($\Delta P \times \dot{m}$). (b) MWCNT ($f \times Re$). Source: Author's own.

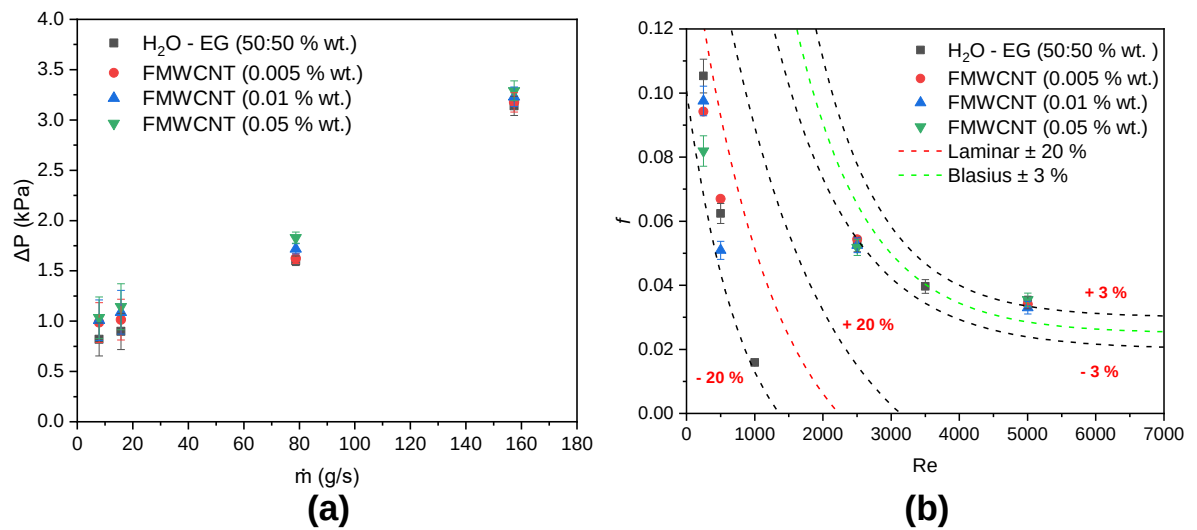


Figure 4.26 – Pressure loss and friction factor for FMWCNT nanofluid samples. (a) FMWCNT ($\Delta P \times \dot{m}$). (b) FMWCNT ($f \times Re$). Source: Author's own.

The results emphasize the need to carefully consider the flow regime and nanoparticle concentration when utilizing nanofluids for thermal management applications. While nanofluids offer potential benefits in heat transfer, their impact on pressure drop and friction factor, particularly in laminar flows, must be accounted for to optimize system performance (EVERTS et al., 2022).

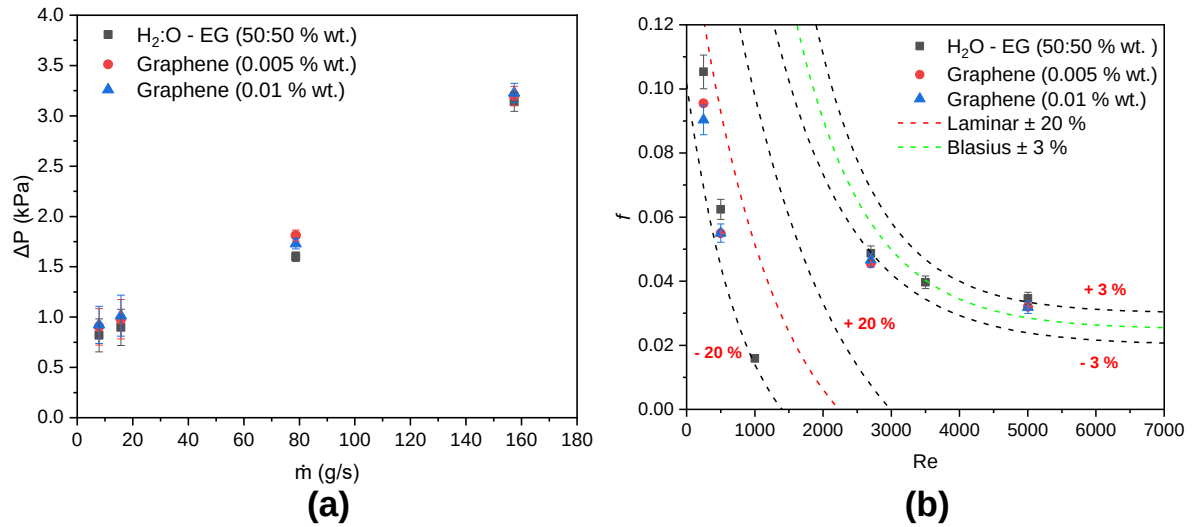


Figure 4.27 – Pressure loss and friction factor for graphene nanofluid samples. (a) Graphene ($\Delta P \times \dot{m}$). (b) Graphene ($f \times Re$). Source: Author's own.

4.4.2 Nanofluid flowing under contraction

When the nanofluid flows through a sudden contraction, there is a notable increase in velocity, leading to higher pressure drop compared to that in an equivalent straight pipe. In cases of sharp or sudden contractions, the flow behavior involves two recirculation regions: one before and one after the contraction. The dissipation of energy within these recirculation zones implies that not all pressure drop converts into kinetic energy, necessitating consideration of both reversible and irreversible pressure drop components.

To harness kinetic energy from pressure effectively, a more gradual change in diameter should be employed to mitigate recirculation and associated pressure losses. The section where fluid flow is at a minimum and velocity is at a maximum is termed the "vena contracta." Downstream of this point, the sudden contraction effect gradually diminishes until it becomes negligible, leading to a phenomenon known as "relaminarization," which occurs when mechanical energy losses are nearly fully converted into friction losses. Typically, this happens beyond a certain distance termed the "relaminarization length," after which friction losses become directly proportional to the length of the channel.

Fig. (4.28a) and Fig. (4.28c) depict the pressure drop for MWCNT nanofluids flowing at contraction ratios (CR) of 1.4 and 1.9 respectively. It is evident that the pressure drop increases with higher mass fraction, mass flow rate, and contraction ratio. For MWCNT nanofluids flowing at CR = 1.4, there is a 15 % increase in pressure drop for the sample with 0.005 % wt.

and a 26 % increase for the sample with 0.01 % wt. compared to the base fluid. At CR = 1.9, the pressure drop enhancement relative to the base fluid is 17% for the sample with 0.005 % wt. and 33 % for the sample with 0.01 % wt. This trend indicates that pressure drop increases with higher contraction ratios and mass fractions, primarily due to the associated increase in viscosity.

Fig. (4.28b) and Fig. (4.28d) display the friction factor for MWCNT samples with CR = 1.4 and CR = 1.9, respectively as a function of Reynolds number. While the pressure drop increases with higher mass flow rates, the friction factor follows an inverse relationship with the square of the mass flow rate (as per Eq. (3.9)), leading to a decrease in the friction factor with increasing Reynolds number. For both cases, the friction factor exhibited mean deviations of 20 % and 3 % from the laminar correlation and Blasius model respectively in the turbulent flow.

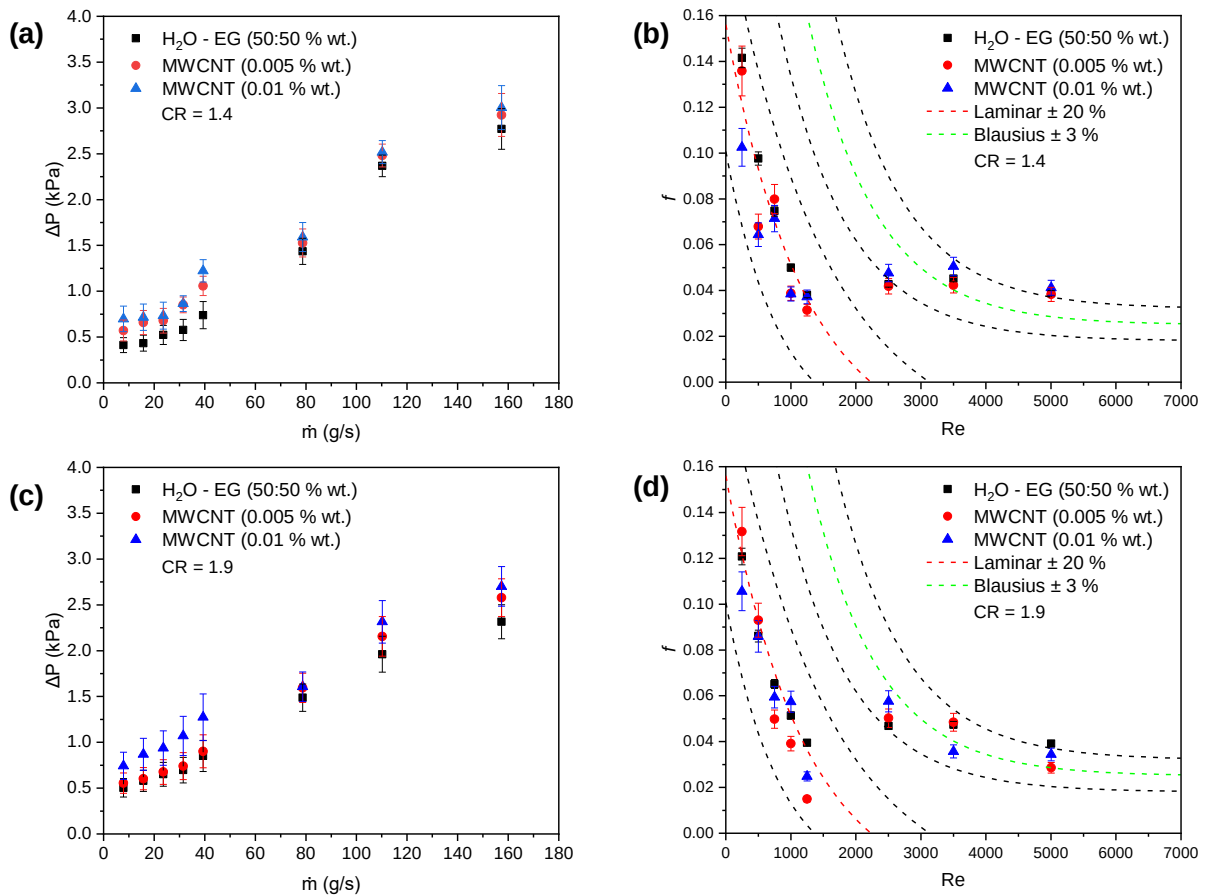


Figure 4.28 – Pressure loss and friction factor for MWCNT nanofluid samples at CR = 1.4. (a) MWCNT ($\Delta P \times \dot{m}$). (b) MWCNT ($f \times Re$). CR = 1.9. (c) MWCNT ($\Delta P \times \dot{m}$). (d) MWCNT ($f \times Re$). Source: Author's own.

Fig. (4.29a – 4.29d) shown the results of pressure drop and friction factor for FMWCNT at CR = 1.4 and CR = 1.9. The addition of oleic acid as a superficial treatment, results in an increase in viscosity and subsequently enhances the pumping power required for the flow, leading to a higher pressure drop compared to MWCNT samples without oleic acid. In the laminar flow, the friction factor for FMWCNT samples exhibited enhancements of 18 % and 25 % for nanofluids with mass fractions of 0.005 % and 0.01 % respectively, relative to the base fluid. In comparison, MWCNT nanofluids at the same mass concentrations showed enhancements of 9 % and 16 % respectively, relative to the base fluid, at the laminar flow. According to (AZIZI et al., 2016; BILAL, 2023; HO et al., 2021), although the friction factor increases when the base fluid is replaced by the nanofluid, incorporating small fractions of nanoparticles in the suspension can result in improved thermohydraulic performance of the flow, especially at higher flow rates.

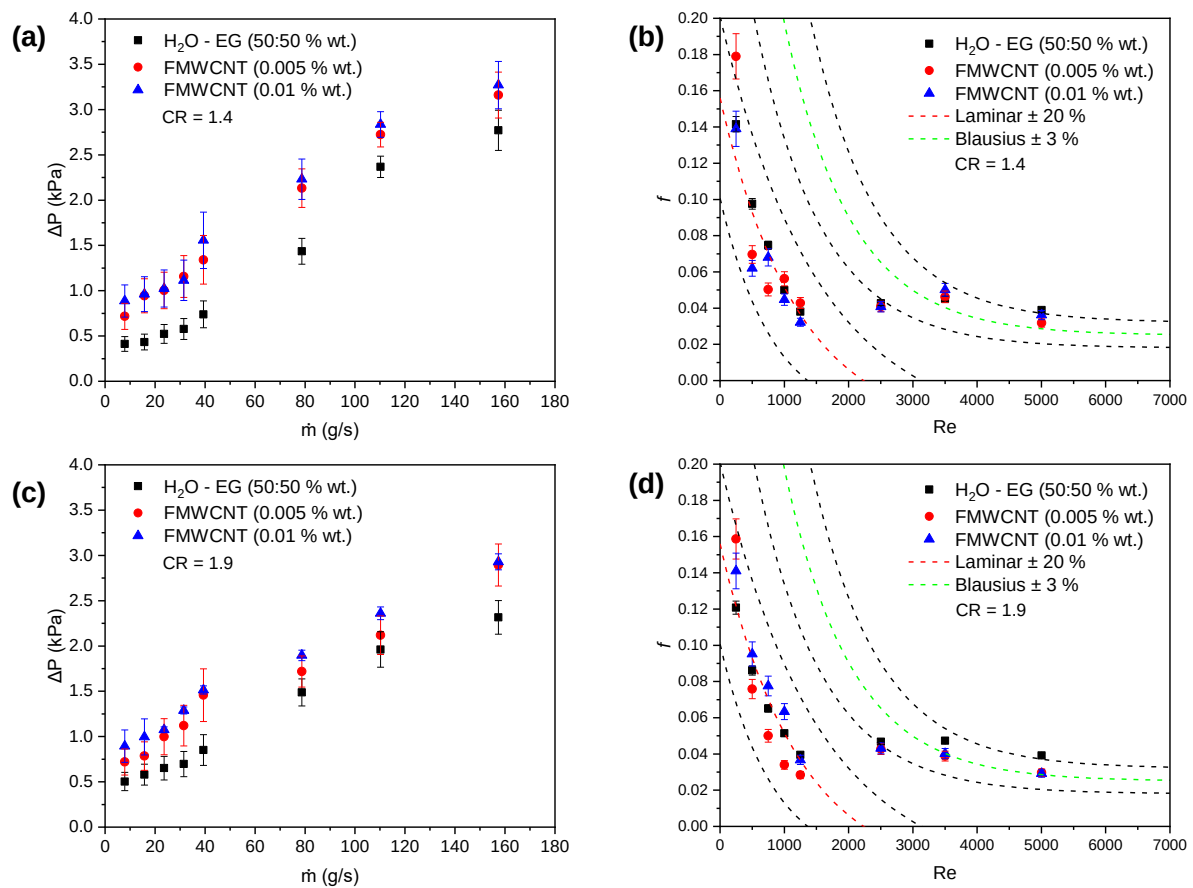


Figure 4.29 – Pressure loss and friction factor for FMWCNT nanofluid samples at CR = 1.4. (a) FMWCNT ($\Delta P \times \dot{m}$). (b) FMWCNT ($f \times Re$). CR = 1.9. (c) FMWCNT ($\Delta P \times \dot{m}$). (d) FMWCNT ($f \times Re$). Source: Author's own.

Fig. (4.30a – 4.30d) shown the results of pressure drop and friction factor for graphene at CR = 1.4 and CR = 1.9. For CR = 1.4, pressure drop increments for graphene samples with mass fractions of 0.005 % and 0.01 % were 15 % and 25 %, respectively, compared to the base fluid. In laminar flow, the friction factor increased by 5 % and 9 % for nanofluids with mass fractions of 0.005 % and 0.01 %, respectively. At CR = 1.9 the pressure drop increments were 13.6 % and 27.5 %, respectively for mass fractions of 0.005 % and 0.01 % respectively, compared to the base fluid, while the friction factor increments relative to the base fluid for graphene samples at same mass fractions showing values of 25.5 % and 62.9 %, respectively.

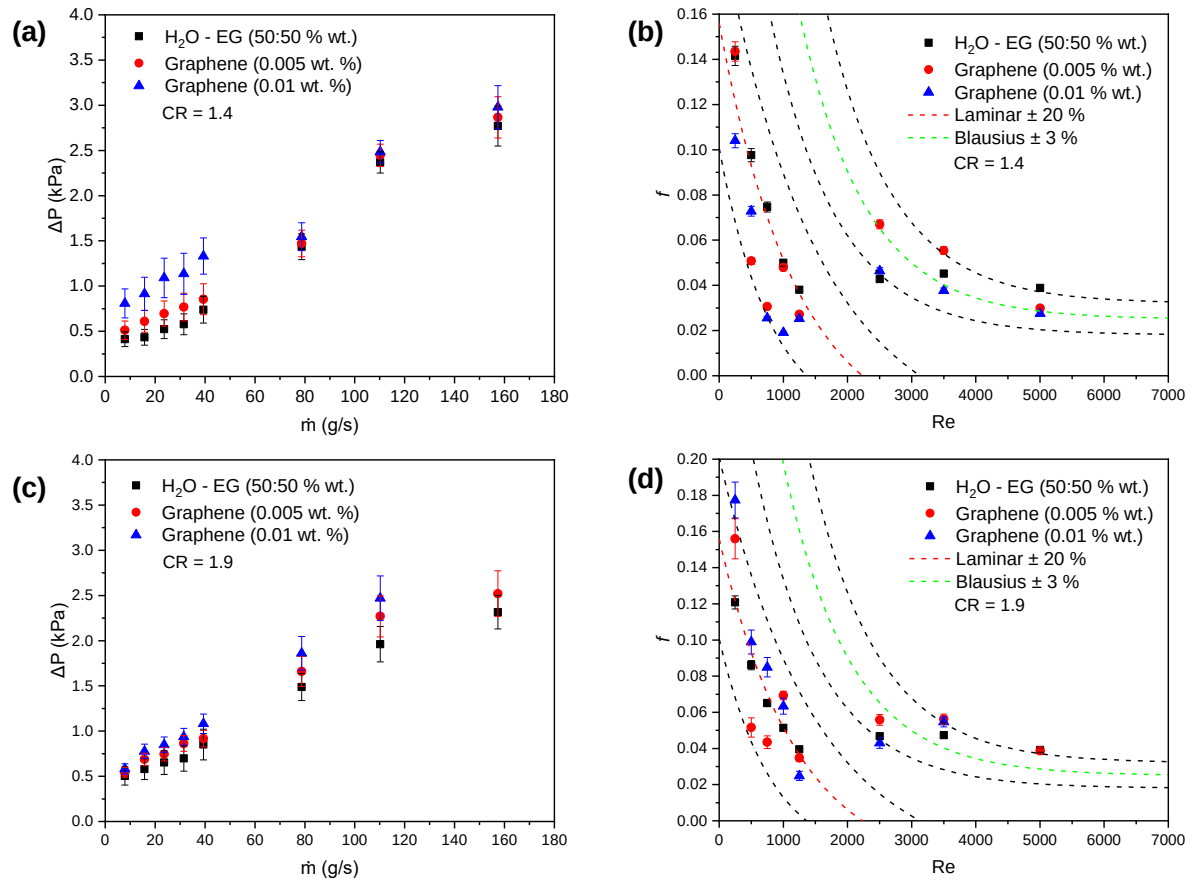


Figure 4.30 – Pressure loss and friction factor for Graphene nanofluid samples at CR = 1.4. (a) Graphene ($\Delta P \times \dot{m}$). (b) Graphene ($f \times Re$). CR = 1.9. (c) Graphene ($\Delta P \times \dot{m}$). (d) Graphene ($f \times Re$). Source: Author's own.

The friction factor is significantly influenced by the density of the nanofluid, which increases with the mass fraction of nanoparticles in the base fluid. Compared to MWCNT and FMWCNT nanofluids, graphene nanofluids require less pumping power, and their viscous drag

effects are less pronounced. Graphene nanofluids exhibit a superior lubrication effect, leading to a lower friction factor (NATESAN and KARINKA, 2023). This reduction in friction for graphene nanofluids can be attributed to an increase in the layer number, leading to adhesion force reduction and thus reduced friction (LIU et al., 2020).

4.4.3 Nanofluid flowing under expansion

Figs (4.31a), (4.32a) and (4.33a) present the pressure drop for nanofluid samples of MWCNT, FMWCNT, and industrial graphene in the test section with an expansion ratio of 1.7 ($ER = 1.7$) as a function of the mass flow rate, $\dot{m}[g/s]$. The experimental pressure drop results for all nanofluid samples analyzed showed that a increment with the increase of Reynolds number, especially for the highest concentrated samples: $\sim 41.78\%$ for MWCNT, $\sim 48.42\%$ for FMWCNT and $\sim 44.8\%$ for industrial graphene. According to (MU'AZ MUHAMMAD *et al.*, 2019), the increase in pressure drop could be attributed to the increased velocity caused by higher concentration and viscosity, along with the expansion and contraction of the flow passage, which disrupts the boundary layer and improves heat transfer. As the Reynolds number increases, the effect of these enhanced properties becomes more significant, resulting in a higher pressure drop. The increased viscosity is important in confined flows where higher shear rates intensify pressure losses (MUKESH KUMAR and CHANDRASEKAR, 2021; OLIVEIRA et al., 2021).

Figs (4.31b), (4.32b) and (4.33b) present the friction factor for nanofluid samples of MWCNT, FMWCNT, and industrial graphene in the test section, plotted against the Reynolds number (Re). These results are compared with the models outlined in the Eq. (3.10) and Eq. (3.11) for laminar and turbulent flows, respectively. In the laminar flow regime, all samples exhibited an average deviation of about 20 % from the theoretical model. However, in the turbulent regime, the experimental results deviated from the Blasius model by approximately 3 % on average across all cases. These deviations suggest that while existing models provide a good approximation, the unique characteristics of nanofluids, such as their particle interactions, can lead to variations that need to be considered in practical applications (CHAKRABORTY and PANIGRAHI, 2020; DEY and SAHU, 2021; WANG et al., 2023).

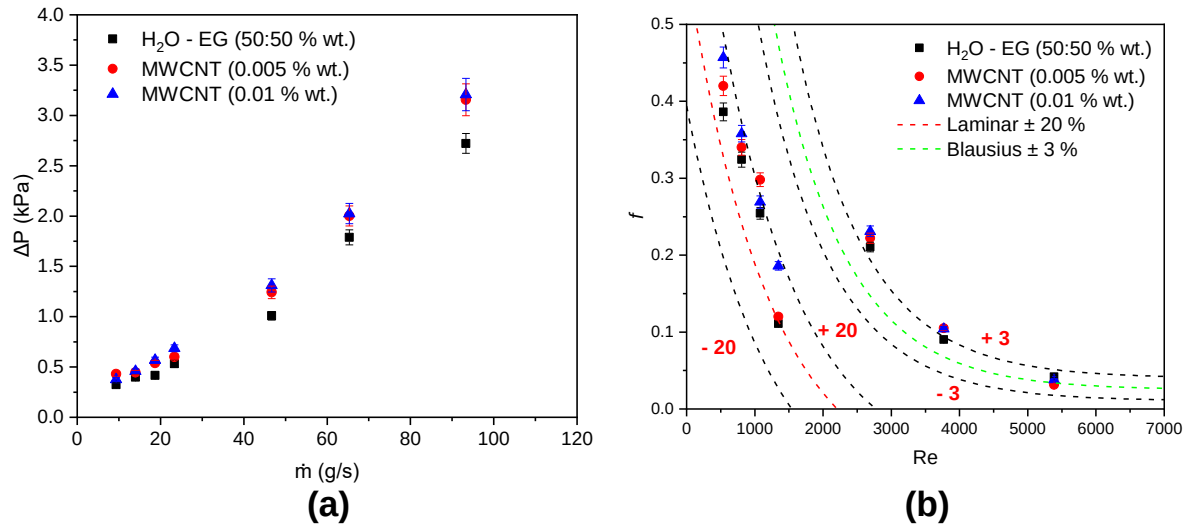


Figure 4.31 – Pressure loss and friction factor for MWCNT nanofluid samples flowing under expansion (ER = 1.7). (a) MWCNT ($\Delta P \times \dot{m}$). (b) MWCNT ($f \times Re$). Source: Author's own.

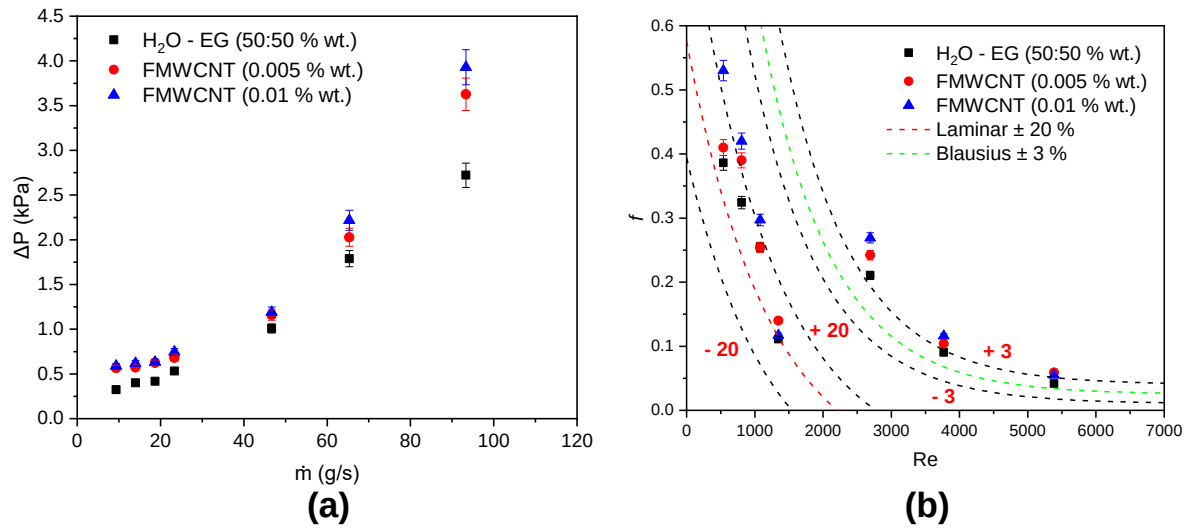


Figure 4.32 – Pressure loss and friction factor for FMWCNT nanofluid samples flowing under expansion (ER = 1.7). (a) FMWCNT ($\Delta P \times \dot{m}$). (b) FMWCNT ($f \times Re$). Source: Author's own.

Among the three nanofluids, FMWCNT exhibits the highest increase in pressure drop, followed by industrial graphene and MWCNT. This result is consistent with the finds reported by (BALAGA et al., 2023), who noted that functionalized nanomaterials, like FMWCNT, exhibit higher interaction with the base fluid, leading to increased effective viscosity and, consequently, greater pressure drop. Industrial graphene, while showing a higher pressure drop

than MWCNT, does not reach the levels observed for FMWCNT, possibly due to its larger particle size and lower surface interaction as noted by (OLIVEIRA et al., 2021).

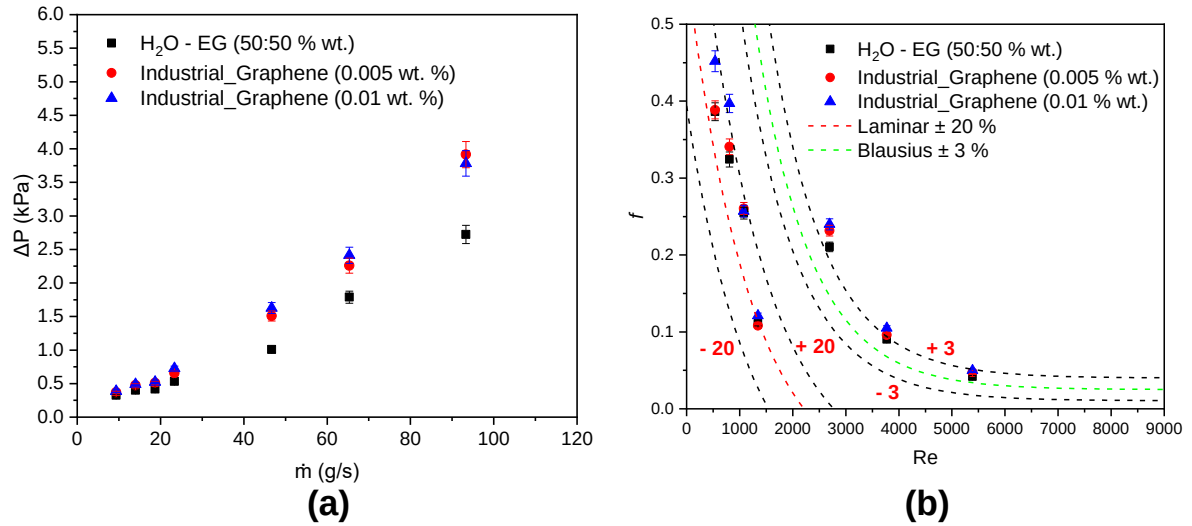


Figure 4.33 – Pressure loss and friction factor for industrial graphene nanofluid samples flowing under expansion (ER = 1.7). (a) Industrial graphene ($\Delta P \times \dot{m}$). (b) Industrial graphene ($f \times Re$). Source: Author's own.

The expansion ratio significantly influences both pressure drop and friction factor, emphasizing the importance of considering flow geometry in the design and optimization of nanofluid based systems. The increased pressure drop and specific friction factor trends observed highlight the need for accurate modeling and prediction tools that can take into account the complex interaction between nanoparticle properties, fluid dynamics and flow geometry. (ALIZADEH et al., 2020a; SAFAEI et al., 2021a; SUN and ZHANG, 2016) emphasizing the critical role of expansion in dictating the performance of nanofluids in practical applications.

4.5 Thermohydraulic performance

4.5.1 Nanofluid flowing in a straight pipe

According to (ALKASMOUL et al., 2022), although nanofluids positively affect thermal performance, they are associated with an increased cost due to the increased pumping power as a result of higher-pressure drops. Thermophysical properties such as thermal conductivity, viscosity, and shape of nanoparticles significantly affect the thermohydraulic performance of

the nanofluid as cooling fluids in heat exchange equipment due to the increase of friction factor leading to an undesirable enhancement of pumping power as described by (ALMURTAJI et al., 2020; KAOOD and HASSAN, 2020). In this context, the thermohydraulic performance of all nanofluid samples was evaluated by considering the enhancement of the convective heat transfer coefficient as a function of pumping power ($\dot{W}_P$), as described by Eq. (4.1). Here, $\dot{m}$ is the mass flow rate, ΔP is the pressure drop, and ρ is the fluid density.

$$\dot{W}_P = \frac{\dot{m} \cdot \Delta P}{\rho} \quad (4.1)$$

The results for straight pipe case obtained are shown in Fig. (4.34a) and (4.34b) for nanoparticle mass fractions of 0.005 % and 0.01 %, respectively, suspended in the base fluid. Which illustrate the relationship between the enhancement of the convective heat transfer coefficient and the pumping power. The results indicate that while there is an increase in pumping power due to the elevated pressure drops, this is a necessary trade-off for achieving enhanced thermal performance.

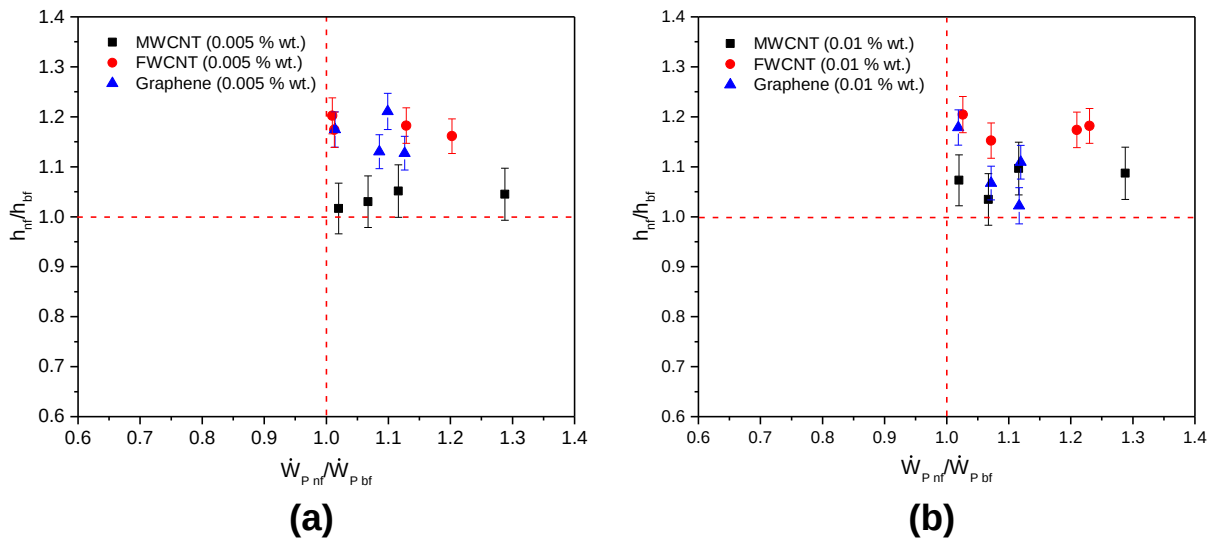


Figure 4.34 – Experimental results of the thermohydraulic performance for the straight pipe case of samples with (a) 0.005 % wt. and (b) 0.01 % wt. Source: Author's own.

As can be seen in Fig. (4.34a) and (4.34b), both the MWCNT samples, with mass fractions of 0.005 % and 0.01 %, have low benefit as a heat transfer fluid due to the thermohydraulic performance for most of the experimental data present a high increment in

relative pumping power and low increments in relative heat transfer coefficient. However, the graphene sample, with a mass fraction of 0.005 %, showed the best thermohydraulic performance because it presented enhancement in the convective heat transfer coefficient, with a maximum increment above 20 %, and the increases in pump power were lower than 15 %.

It can be seen in Fig. (4.34a) and (4.34b) that four quadrants described the thermohydraulic behavior of the nanofluids. Here, the “y-axis” is the relative convective heat transfer coefficient, and the “x-axis” is the relative pumping power, where quadrant (1,1) represents the base fluid used. The first quadrant ($x\text{-axis} > 1$, $y\text{-axis} > 1$) represents the nanofluid thermohydraulic behavior enhancing convective heat transfer and pumping power. It is important to highlight that the best performance for any nanofluid would be $x\text{-axis} = 1$, $y\text{-axis} > 1$. The second quadrant ($x\text{-axis} < 1$, $y\text{-axis} > 1$) and the third quadrant ($x\text{-axis} < 1$, $y\text{-axis} < 1$) are improbable quadrants to describe the thermohydraulic performance of nanofluids due to the dependence of the pumping power on the pressure drop, which is higher for the nanofluid. The fourth quadrant ($x\text{-axis} > 1$, $y\text{-axis} < 1$) does not represent any advantage for the nanofluid application since it represents higher pumping power values and lower heat transfer coefficients than the base fluid at the same nominal conditions. This same analysis can be applied for the nanofluid flowing under contraction or expansion.

4.5.2 Nanofluid flowing under contraction

The experimental analysis of thermohydraulic performance in closed conduits with sudden contractions revealed that higher Reynolds numbers require more pumping power for geometries with higher contraction ratios to achieve similar heat transfer enhancements. (AL-DAMOOK and AZZAWI, 2021) suggest that reducing the contraction ratio at the same heat flux increases local thermohydraulic performance. Nanofluids exhibit improved thermal performance in closed conduits due to their superior thermophysical properties compared to traditional cooling fluids. While nanofluids with high mass fractions can enhance thermal conductivity, increasing the mass fraction can lead to poor stability and nanoparticle agglomeration, ultimately resulting in lower thermal performance (GAO *et al.*, 2023).

Fig. (4.35a-4.35d) depict the current findings of thermohydraulic performance for nanofluids flowing at CR = 1.4 and CR = 1.9 with mass fractions of 0.005 % wt. and 0.01 % wt., dispersed in the base fluid. All nanofluid samples were evaluated by considering the enhancement of the convective heat transfer coefficient as a function of pumping power ($\dot{W}_P$). The contraction in the flow channel results in a higher pressure drop due to the increased flow velocity and the

associated viscous effects, leading to an additional demand of pumping power to maintain the flow rate (GÜCÜYEN et al., 2019; GUO et al., 2010; ROUL and DASH, 2011a). For nanofluids, which typically have higher viscosity than the base fluid, this effect is more pronounced.

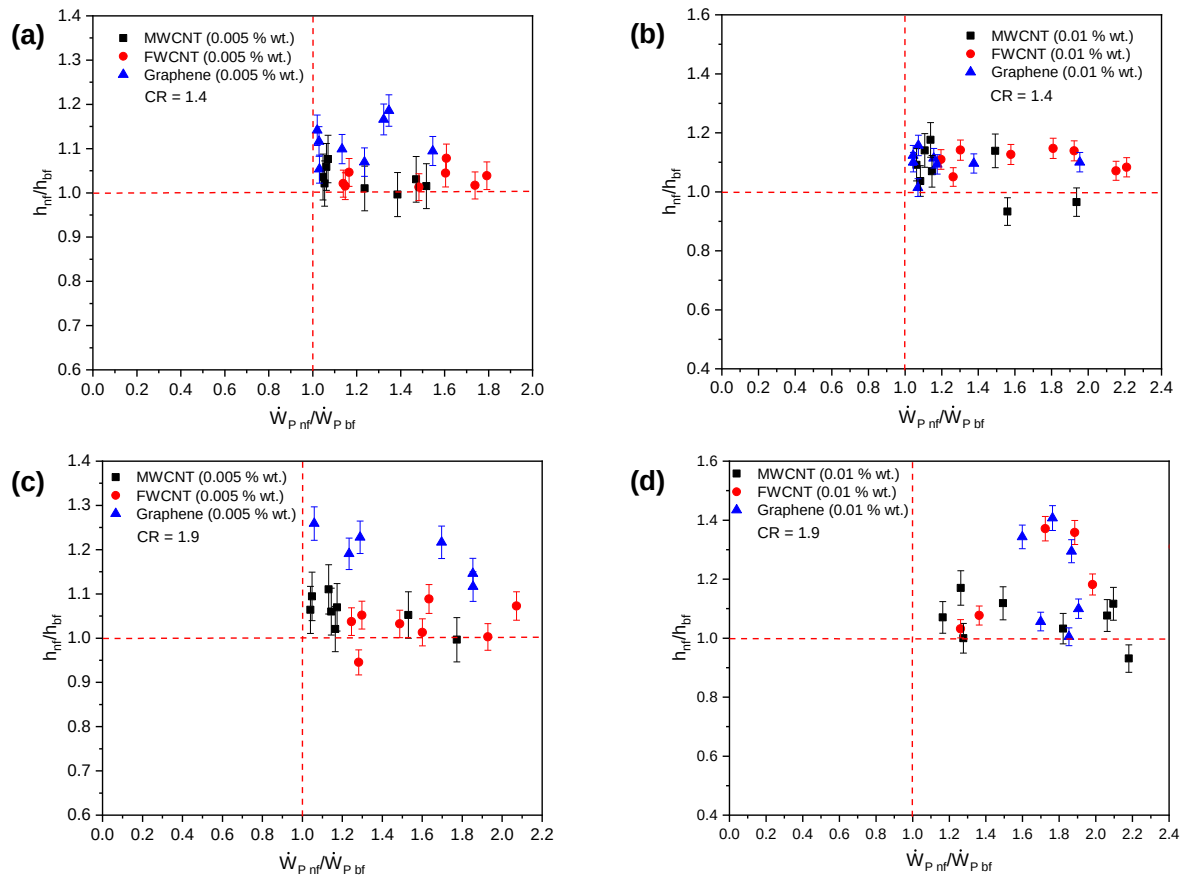


Figure 4.35 – Thermal - hydraulic performance results of samples for CR = 1.4 with: (a) 0.005 % wt. and (b) 0.01 % wt. For CR = 1.9. (c) 0.005 % wt. and (d) 0.01 % wt. Source: Author's own.

The thermohydraulic performance results demonstrate the most favorable trends for MWCNT and graphene with the less concentrated samples (0.005 % wt.) at CR = 1.4. Conversely, FMWCNT exhibited a higher pumping power requirement to achieve a similar heat transfer obtained by MWCNT and graphene under the same conditions. The viscous effect of FMWCNT nanofluids led to an increase in pressure drop in the flow and, consequently, a greater pumping power requirement, impairing heat transfer. The thermal performance enhancements of MWCNT, FMWCNT, and graphene nanofluids in relation to the base fluid were on 3.1 %, 3.4 %, and 11.6 %, respectively, with a mass fraction of 0.005 % wt. For

MWCNT, FMWCNT, and graphene nanofluids flowing at $CR = 1.9$, a thermal enhancement of 3.05 %, 5.8 %, and 11.71 % with a mass fraction of 0.005 % wt. was reported.

The thermohydraulic performance of nanofluids flowing through a contraction is characterized by enhanced heat transfer due to increased velocity and improved thermal conductivity as reported by (AL-OBAIDI, 2024; AL-SAMMARRAIE and VAFAI, 2019; GÜRSOY *et al.*, 2024). However, this comes at the cost of a higher pressure drop, necessitating more pumping power. The overall performance depends on optimizing the fluid properties to maximize heat transfer while minimizing the energy required to pump the fluid through the contraction. As indicated by the results, a high contraction ratio generates an early transition to turbulence with better heat transfer and a higher pressure drop at lower Reynolds numbers. However, overall heat transfer improves with the increment of the contraction ratio, Reynolds, and Prandtl numbers.

4.5.3 Nanofluid flowing under expansion

Sudden expansion geometry is crucial in engineering designs, particularly in heat exchangers. In these configurations, heat transfer is most effective at the reattachment points, while it significantly diminishes in the recirculation zones formed by the fluid (GÜRSOY *et al.*, 2022). Nanoparticles like MWCNTs, FMWCNTs, and graphene have higher thermal conductivities than conventional base fluids. When the nanofluid samples flow through a sudden expansion, the turbulent mixing is intensified due to the increased momentum and velocity fluctuations of the nanoparticles (PAZARLIOĞLU *et al.*, 2024). This enhanced turbulence improves the convective heat transfer, particularly near the reattachment points where the flow re-establishes after separation (TOGUN *et al.*, 2016a).

Figs. (4.36a) and (4.36b) depict the current findings of thermohydraulic performance for nanofluids flowing at $ER = 1.7$ with mass fractions of 0.005 % wt. and 0.01 % wt., dispersed in the base fluid. All nanofluid samples were evaluated by considering the enhancement of the convective heat transfer coefficient as a function of pumping power ($\dot{W}_P$).

The thermal performance enhancements of MWCNT, FMWCNT, and graphene nanofluids in relation to the base fluid were on averaged 6.1 %, 7.2 %, and 4.2 %, respectively, with a mass fraction of 0.005 % wt. For the mass fraction of 0.01 % wt., the thermal performance enhancements of MWCNT, FMWCNT, and graphene nanofluids in relation to the base fluid averaged 8.1 %, 5.6 %, and 5 %, respectively.

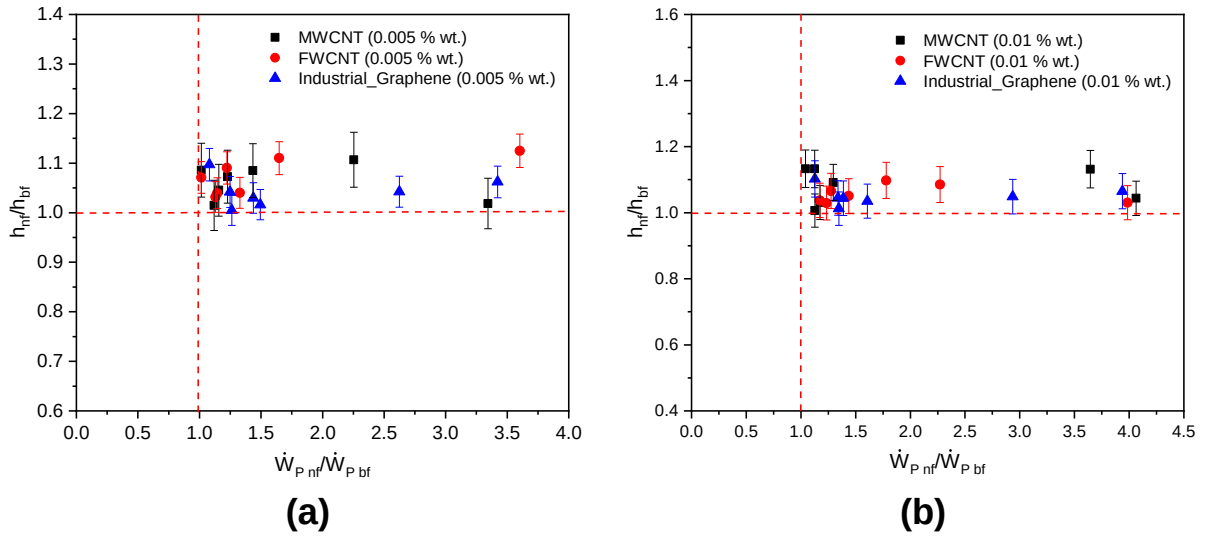


Figure 4.36 – Thermal - hydraulic performance results of nanofluid samples for ER = 1.7 with: (a) 0.005 % wt. and (b) 0.01 % wt. Source: Author's own.

As can be noted, the thermohydraulic performance results demonstrate the most favorable trends for MWCNT with the less concentrated samples (0.005 % wt.) at ER = 1.7. Conversely, FMWCNT and industrial graphene exhibited a higher pumping power requirement to achieve a similar heat transfer obtained by MWCNT under the same conditions. The viscous effect of FMWCNT and industrial graphene nanofluids led to an increase on pressure drop in the flow and, consequently, a greater pumping power requirement, impairing heat transfer as observed by (ALIZADEH *et al.*, 2020a; AWAIS *et al.*, 2021; GÜRSOY *et al.*, 2024; KIMOUCHE *et al.*, 2017). The highest increments in pumping power when nanofluids flow under expansion are primarily due to the increased pressure drop around the expansion region (ALRASHED *et al.*, 2018). This is exacerbated by the higher viscosity and density of the nanofluid compared to the base fluid. When a fluid experiences sudden expansion, the flow undergoes separation and reattachment, which creates zones of recirculation and turbulence (AL-GAILANI, 2018). These factors increase the pressure drop and, consequently, the pumping power required to maintain the flow rate. Furthermore, the enhanced turbulence due to the momentum and velocity fluctuations of the nanoparticles increases the convective heat transfer at the cost of higher pressure drops, which could explain the trade-off between thermal performance and pumping power.

4.6 Mathematical models proposed for thermophysical properties

4.6.1 Thermal conductivity model

Based on the experimentally obtained thermal conductivity data for nanofluid samples based on H₂O-EG 50:50 % wt. mixture, a mathematical model, outlined in Eq. (4.2), was proposed to predict this physical property. The model incorporates the influence of nanoparticle concentration, as well as the thermal conductivities of the base fluid and the nanoparticles. Additionally, the model relies on two constants, C_1 and C_2 , detailed in Table 4.4, which account for the potential effects of the nanoparticle shape and size.

$$k_{nf}(k_{bf}, k_{np}, \varphi) = \left(1 + \frac{k_{np}}{C_1} \cdot \varphi^{C_2}\right) \cdot k_{bf} \quad (4.2)$$

where k_{nf} is the thermal conductivity of the nanofluid, k_{bf} is the thermal conductivity of the base fluid, k_{np} is the thermal conductivity of the nanoparticle and φ is the mass fraction.

Table 4.4– Thermal conductivity model constants for nanofluid samples based on (H₂O-EG/50:50 % wt.).

Nanofluid	C_1	C_2	R^2
MWCNT/H ₂ O-EG	12220	0.3794	0.9987
FMWCNT/ H ₂ O-EG	33680	0.01364	0.9917
Graphene/H ₂ O-EG	17220	0.1413	0.9660
Industrial graphene/H ₂ O-EG	9404	0.3066	0.9326

Source: Author's own.

The model described in Eq. (4.2) was obtained through curve-fitting using the Marquardt-Levenberg algorithm, as proposed by (MARQUARDT, 1963), and implemented in MATLAB. This method allows for the determination of the coefficients of the independent variables (volumetric concentration and temperature) that provide the best fit by minimizing the sum of the squared differences between the experimental data and the predicted values. Figs. (4.37), (4.38), (4.39) and (4.40) show the comparisons between the experimental thermal conductivity results for the nanofluid samples based on (H₂O - EG 50:50 % wt.) and the results obtained using the proposed correlation presented in Eq. (4.2). Therefore, according to Fig. (4.37) to Fig.

(4.40), the good agreement between the experimental results and those obtained with the thermal conductivity model described in Eq. (4.2) can be observed and verified.

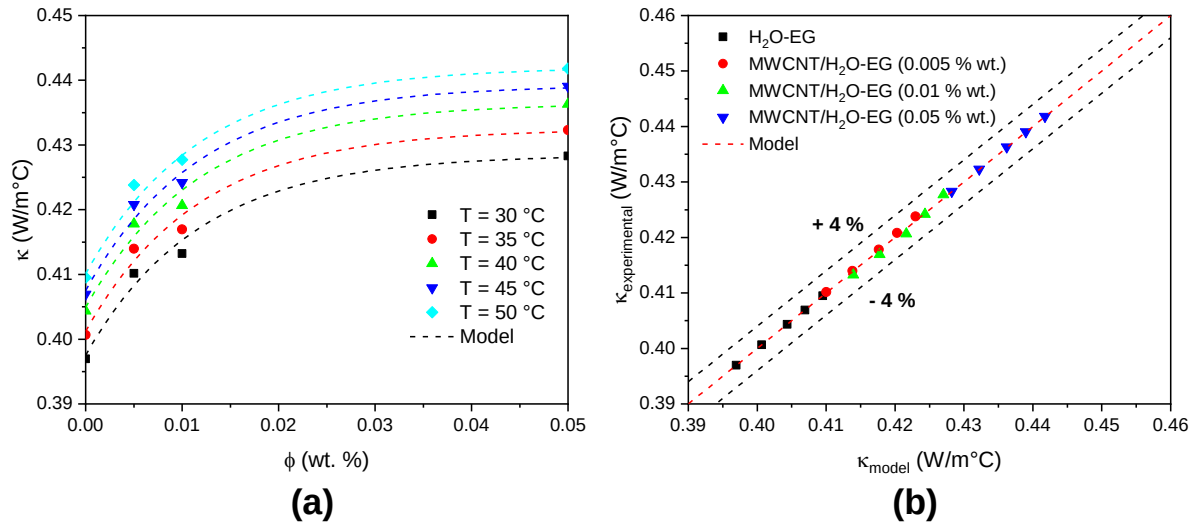


Figure 4.37 – Comparison of experimental data with the proposed mathematical model for thermal conductivity. (a) MWCNT ($\kappa \times \phi$). (b) MWCNT ($\kappa_{\text{exp}} \times \kappa_{\text{model}}$). Source: Author's own.

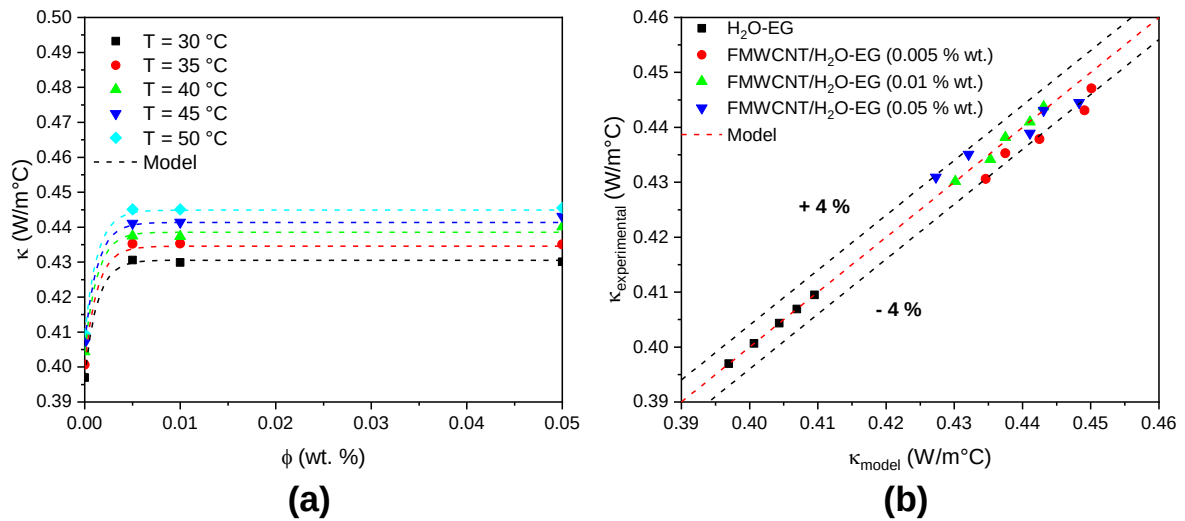


Figure 4.38 – Comparison of experimental data with the proposed mathematical model for thermal conductivity. (a) FMWCNT ($\kappa \times \phi$). (b) FMWCNT ($\kappa_{\text{exp}} \times \kappa_{\text{model}}$). Source: Author's own.

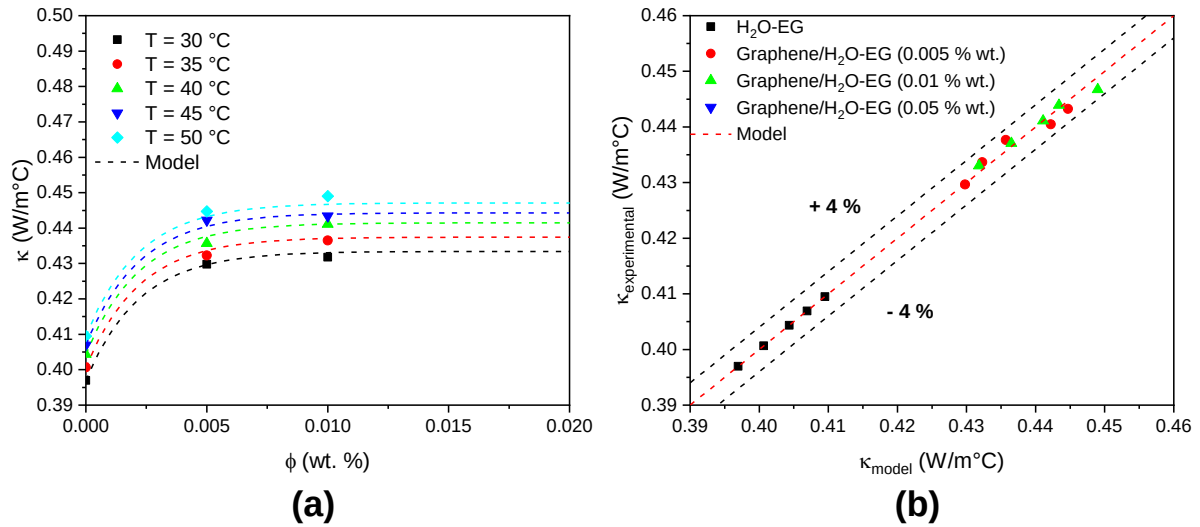


Figure 4.39 – Comparison of experimental data with the proposed mathematical model for thermal conductivity. (a) Graphene ($\kappa \times \phi$). (b) Graphene ($\kappa_{\text{exp}} \times \kappa_{\text{model}}$). Source: Author's own.

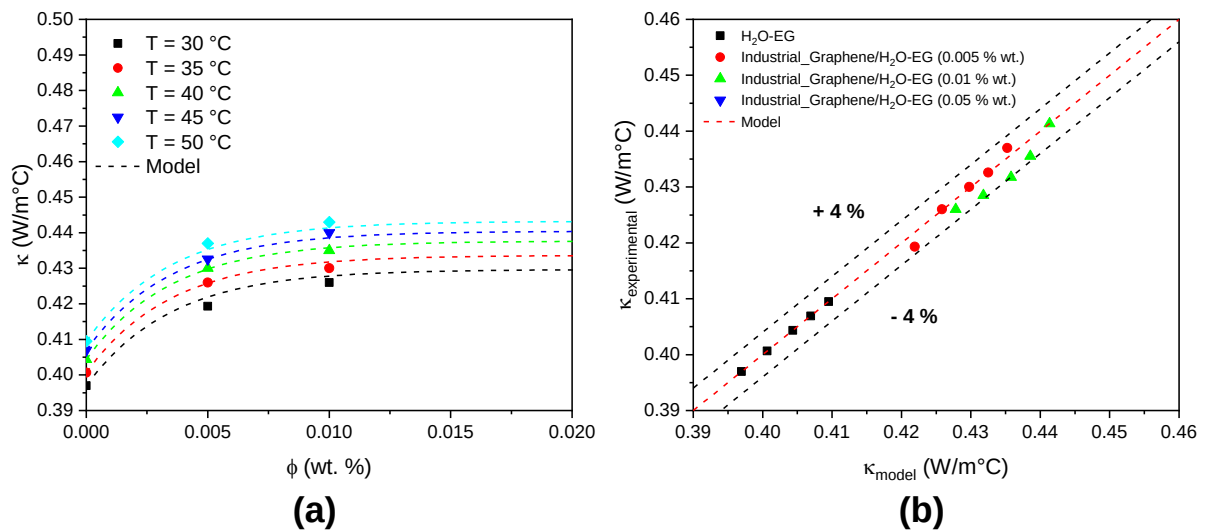


Figure 4.40 – Comparison of experimental data with the proposed mathematical model for thermal conductivity. (a) Industrial graphene ($\kappa \times \phi$). (b) Industrial graphene ($\kappa_{\text{exp}} \times \kappa_{\text{model}}$). Source: Author's own.

4.6.2 Dynamic viscosity model

Based on the experimental dynamic viscosity data for nanofluid samples using a ($\text{H}_2\text{O-EG}$ 50:50 % wt.) base fluid, a mathematical model was developed and presented in Eq. (4.3) to predict the dynamic viscosity of these nanofluids. This model considers the influence of nanoparticle concentration and the viscosity of the base fluid. Additionally, it incorporates a constant, C , which varies for each type of nanofluid as specified in Table 4.5.

$$\mu_{nf}(\mu_{bf}, \varphi) = (1 + C \cdot \varphi) \cdot \mu_{bf} \quad (4.3)$$

where μ_{nf} is the dynamic viscosity of the nanofluid, μ_{bf} is the dynamic viscosity of the base fluid and φ is the mass fraction.

Table 4.5 – Dynamic viscosity model constants for nanofluid samples based on (H₂O-EG/50:50 % wt.).

Nanofluid	C	R^2
MWCNT/H ₂ O-EG	2.456	0.9932
FMWCNT/ H ₂ O-EG	3.344	0.986
Graphene/H ₂ O-EG	3.501	0.999
Industrial graphene/H ₂ O-EG	3.501	0.999

Source: Author's own.

Figs. (4.41), (4.42), (4.43) and (4.44) show the comparisons between the experimental dynamic viscosity results for the nanofluid samples based on (H₂O - EG 50:50 % wt.) and the results obtained using the proposed correlation, presented in Eq. (4.3). Therefore, according to Fig. (4.41) to Fig. (4.44), the good agreement between the experimental results and those obtained with the proposed correlation can be observed and verified.

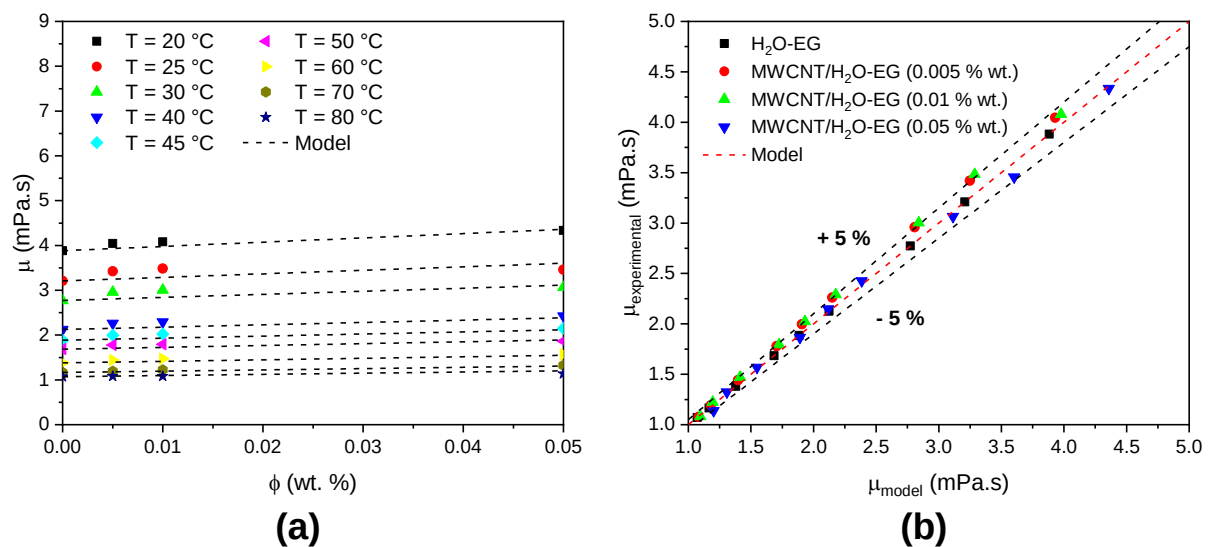


Figure 4.41 – Comparison of experimental data with the proposed mathematical model for dynamic viscosity. (a) MWCNT ($\mu \times \phi$). (b) MWCNT ($\mu_{\text{exp}} \times \mu_{\text{model}}$). Source: Author's own.

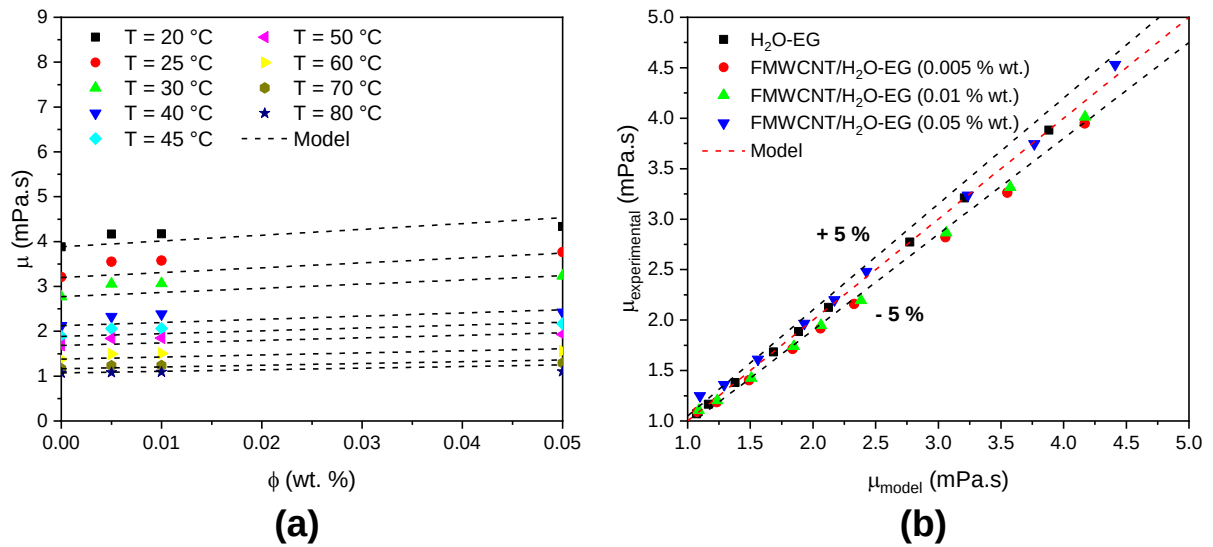


Figure 4.42 – Comparison of experimental data with the proposed mathematical model for dynamic viscosity. (a) FMWCNT ($\mu \times \phi$). (b) FMWCNT ($\mu_{\text{exp}} \times \mu_{\text{model}}$). Source: Author's own.

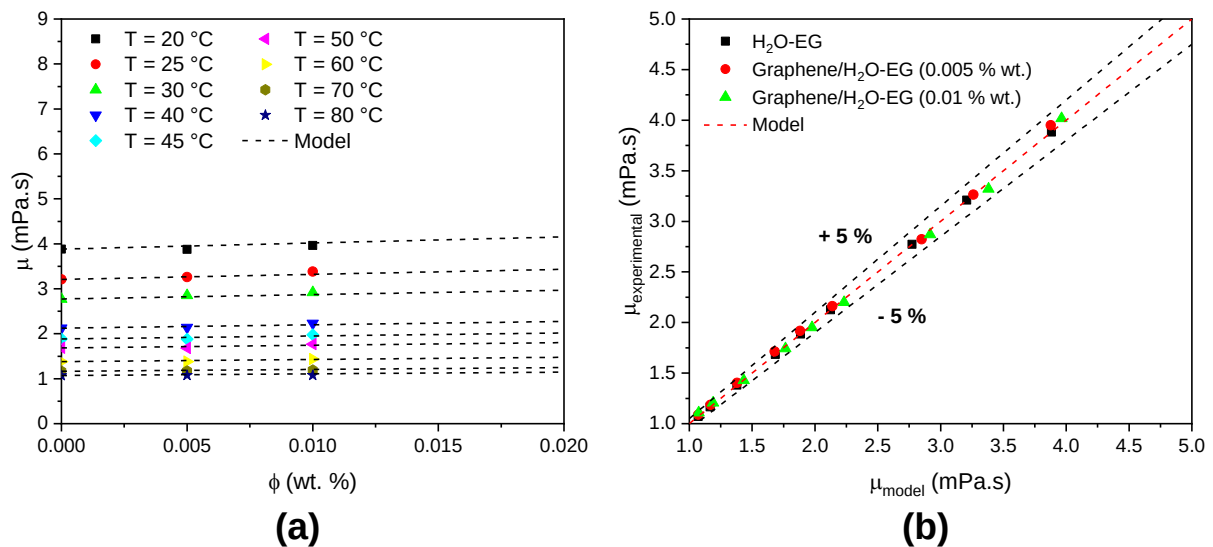


Figure 4.43 – Comparison of experimental data with the proposed mathematical model for dynamic viscosity. (a) Graphene ($\mu \times \phi$). (b) Graphene ($\mu_{\text{exp}} \times \mu_{\text{model}}$). Source: Author's own.

Figs (4.41b), (4.42b), (4.43b) and (4.44b) show a comparison between the experimental results of the dynamic viscosity of the carbon nanotube nanofluid samples and the results of the correlation proposed in Eq. (4.3). There was good agreement with the model used, with a maximum deviation of 5 % from the experimental values. This consistency highlights the effectiveness of the models in predicting both the dynamic viscosity and thermal conductivity of the nanofluid, demonstrating their usefulness and accuracy.

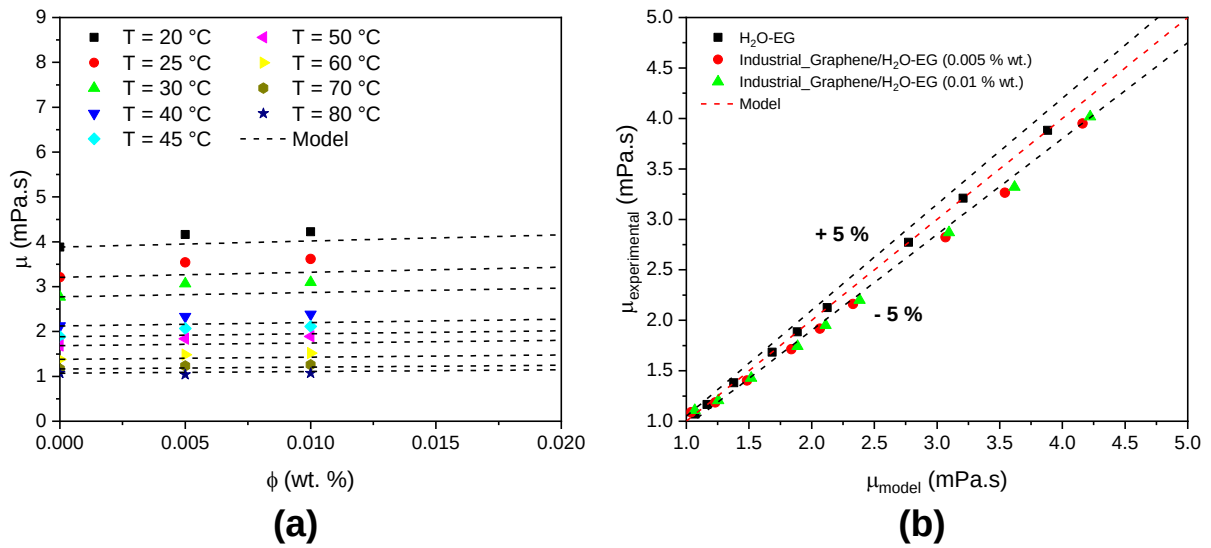


Figure 4.44 – Comparison of experimental data with the proposed mathematical model for dynamic viscosity. (a) Industrial graphene ($\mu \times \phi$). (b) Industrial graphene ($\mu_{\text{exp}} \times \mu_{\text{model}}$). Source: Author's own.

4.7 Mathematical models proposed for convective heat transfer

4.7.1 Heat transfer by convection in turbulent flow for the straight pipe case

The Nusselt number for a given geometry can be expressed in terms of the Reynolds number Re , the Prandtl number Pr , and the space variable “ x ”, and such a relation can be used for different fluids flowing at different velocities over similar geometries of different lengths. This relation is extremely valuable as it states that for a given geometry, the Nusselt number can be expressed as a function of Reynolds and Prandtl numbers alone (BUSCHMANN *et al.*, 2018). Fig. (4.45) presents the comparison between the results of the convective heat transfer coefficient experimentally obtained for nanofluid samples based on (H_2O - EG 50:50 % wt.) in a fully developed turbulent flow regime and the heat transfer coefficient obtained using the Gnielinski correlation (GNIELINSKI, 1975), presented by Eq. (3.16). Table 4.6 shows the average deviation results of the comparison between the classic model and the experimental results of the nanofluid samples based on (H_2O - EG 50:50 % wt.).

Fig. (4.45) shows that the experimental heat transfer data deviated by more than $\pm 30\%$ from the classical model used for comparison. Consequently, based on the average deviations between the experimental heat transfer coefficient and the Gnielinski correlation, as shown in Table 4.6, there is a clear need to propose a mathematical model that better aligns with the

experimental heat transfer results for nanofluid samples based on (H₂O - EG 50:50 % wt.) in fully turbulent flow within a straight horizontal pipe.

The initial step in defining a convective heat transfer model involves establishing the relationship between the heat transfer process and the flow field, primarily characterized by the Reynolds number, as well as the rates of heat and momentum transfer, which are governed by the Prandtl number (Pr). As noted by (HOLMAN, 2009), an exponential correlation for each of these parameters, as presented in the fundamental form in Eq. (4.4), can be utilized to effectively correlate the experimental heat transfer data.

$$Nu_{nf} = C_x \cdot Re_d^m \cdot Pr^n \quad (4.4)$$

where C_x , n , and m were determined based on the experimental data. The exponent of the Prandtl number, n , was set to 0.4 when the fluid was being heated (i.e., $T_p(x) > T_m(x)$), in accordance with the correlation proposed by (DITTUS and BOELTER, 1930) for fully developed turbulent flow in smooth tubes. With the value of n established, the heat transfer data were subsequently analyzed to determine the value of m for the Reynolds number. The constant C_x was introduced to account for the influence of nanoparticle addition on convective heat transfer in the nanofluid samples and was defined according to the model presented in Eq. (4.5).

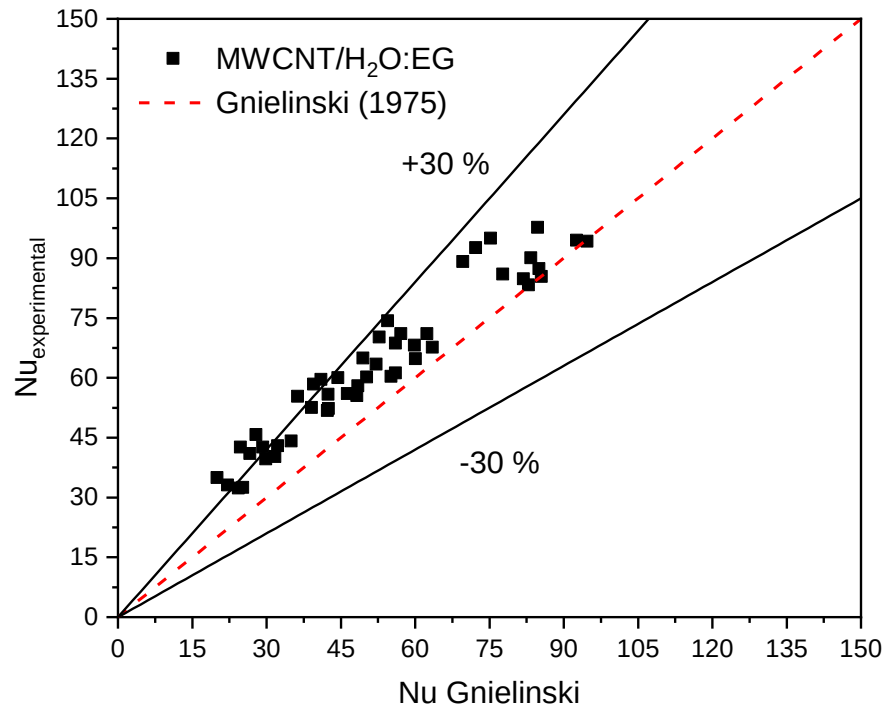
$$C_x = C \cdot (1 + C_{nf} \cdot \varphi^{x_{nf}}) \quad (4.5)$$

where C is a constant independent of the nanofluid type, with a value of 0.0168. Conversely, C_{nf} is a constant specific to the nanofluid type, and φ represents the nanoparticle concentration raised to an exponent x_{nf} , which also varies depending on the type of nanofluid.

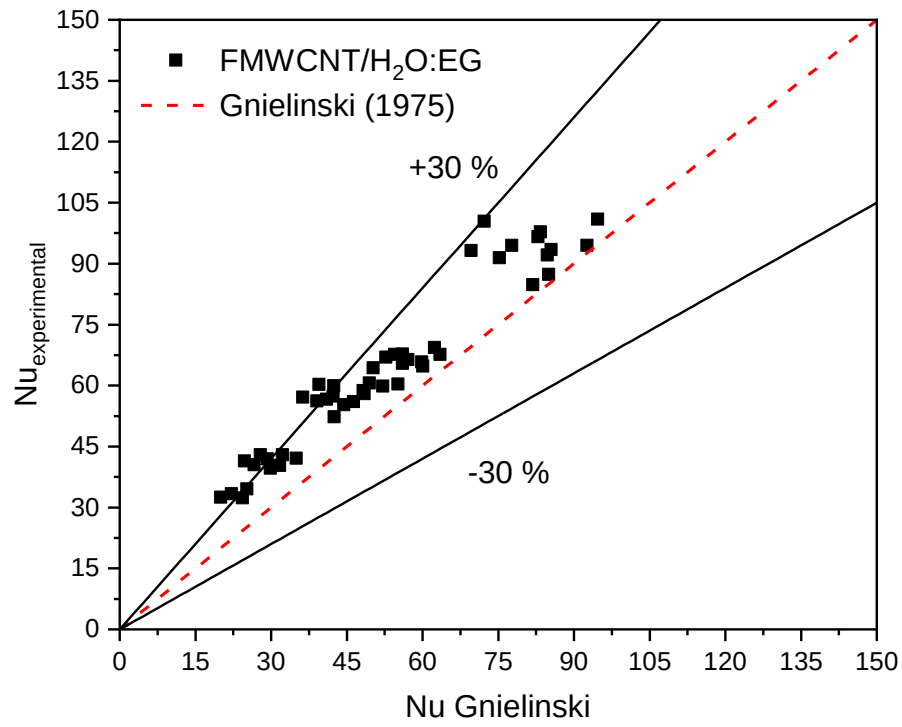
Table 4.6 – Average deviation of experimental data and Gnielinski's model (1975).

Nanofluid	Average deviation presented with Gnielinski's correlation		
	$\varphi = 0.005 \%$	$\varphi = 0.01 \%$	$\varphi = 0.05\%$
MWCNT	20.08 %	28.87 %	36.49 %
FMWCNT	28.71 %	31.83 %	42.54 %
Graphene	25.11 %	28.70 %	[-]

Source: Author's own.



(a)



(b)

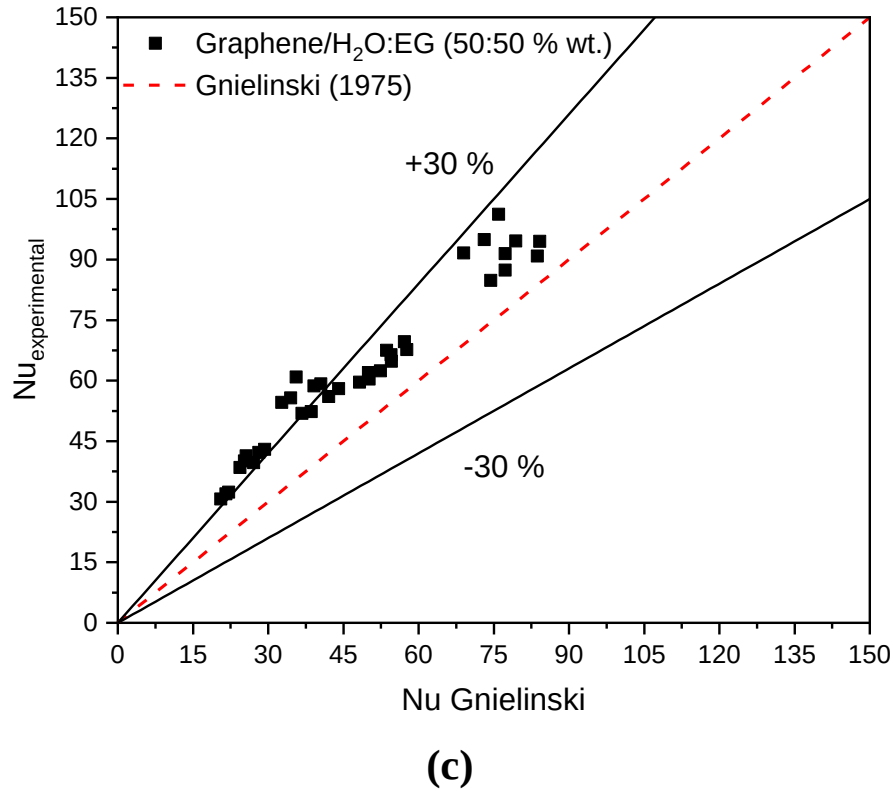


Figure 4.45 – Comparison between the experimental convective heat transfer coefficient and Gnielinski's correlation. (a) MWCNT. (b) FMWCNT. (c) Graphene. Source: Author's own.

Combining Eq. (4.4) and Eq. (4.5), the general model described in Eq. (4.6) was obtained, which correlates the results of convective heat transfer in the turbulent regime of the nanofluid samples based on (H₂O-EG 50:50 % wt.).

$$Nu_{nf} = 0.0168 \cdot (1 + C_{nf} \cdot \varphi^{x_{nf}}) \cdot Re_d^m \cdot Pr^n \quad (4.6)$$

This model is valid for a flow range of $Re \geq 2500$ and nanoparticle concentrations ranging from $0.005 \% \leq \varphi \leq 0.01 \%$. The constants x_{nf} and C_{nf} used in the model presented in Eq. (4.7) are detailed in Table 4.7. Figs. (4.46), (4.47) and (4.48) provides a comparison between the experimentally obtained convective heat transfer coefficients in fully developed turbulent flow and those predicted by the proposed model for MWCNT, FMWCNT and graphene respectively, as described by Eq. (4.7). Also, a comparison with the model and some finds presented in the literature is presented in the figures.

Table 4.8 presents the average deviations obtained from the comparison between the proposed model and the experimental results for the nanofluid samples based on (H₂O - EG

50:50 % wt.). Thus, based on Table 4.8 and Figs (4.46) to (4.48), there is a reasonable agreement between the experimental results and the proposed model for the heat transfer of nanofluids in fully developed turbulent flow in a horizontal straight pipe.

Table 4.7 – Parameters of correlations for the straight pipe case in turbulent flow.

Constant	MWCNT	FMWCNT	Graphene
C_{nf}	1.39	0.7292	7.176
m	0.8399	0.8406	0.8405
x_{nf}	0.6268	0.3527	0.9642

Source: Author's own.

Table 4.8 – Average deviation of experimental data in the turbulent regime and the model described in Eq. 4.6.

Nanofluid	Average deviation presented with proposed correlation		
	$\phi = 0.005 \%$	$\phi = 0.01 \%$	$\phi = 0.05\%$
MWCNT	2.25 %	2.5 %	0.46 %
FMWCNT	1.08 %	0.96 %	0.24 %
Graphene	3.04 %	0.82 %	[-]

Source: Author's own.

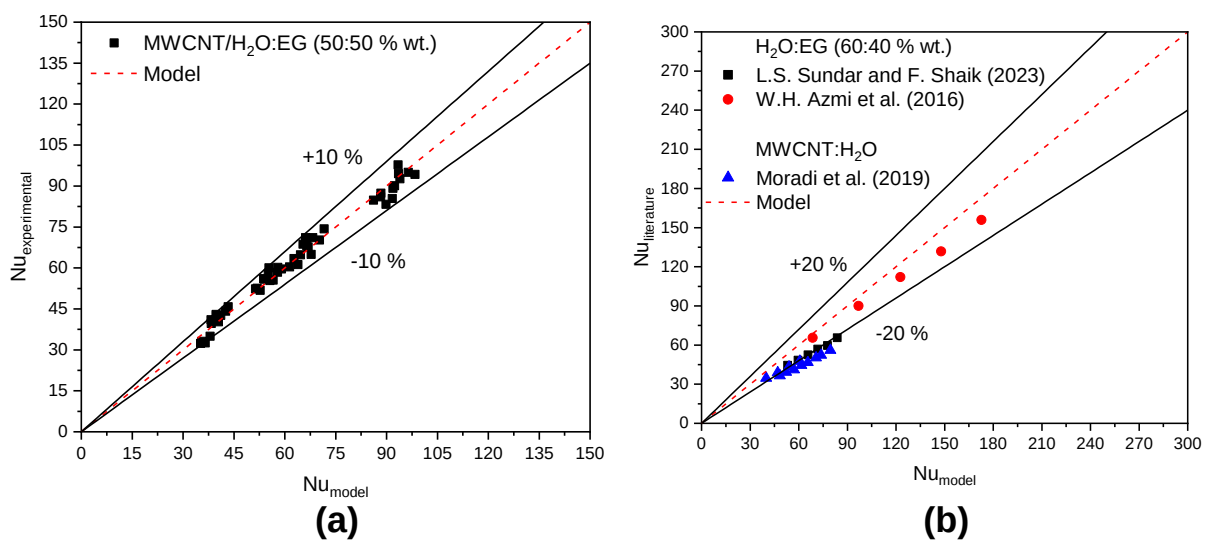


Figure 4.46 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for MWCNT nanofluid samples. (a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.

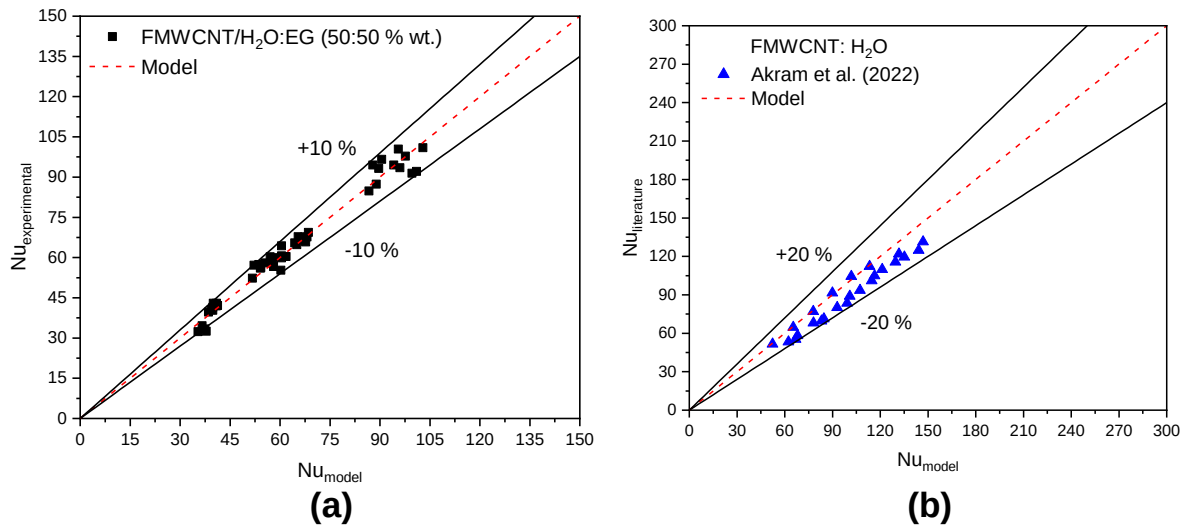


Figure 4.47 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for FMWCNT nanofluid samples. (a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.

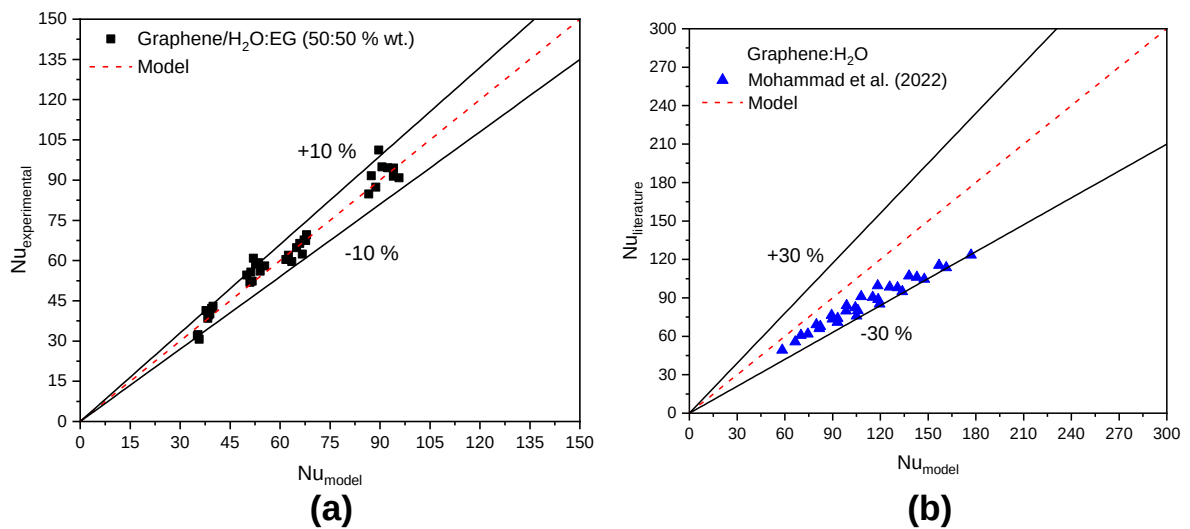


Figure 4.48 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for graphene nanofluid samples. (a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.

Fig. (4.46a) compares the Nusselt number obtained from experiments with the one predicted by the model. The results show that the model is quite accurate, with deviations mostly within $\pm 10\%$ from the experimental data. This suggests that the model effectively captures the heat transfer behavior for MWCNT nanofluid. Fig. (4.46b) compares the proposed model with findings from other studies in the literature (AZMI et al., 2016; MORADI et al.,

2019; SUNDAR and SHAIK, 2023). The model's predictions are within a reasonable range, with deviations from the literature data also within $\pm 20\%$. This indicates the model's robustness and its applicability to various cases.

Fig. (4.47a) shows for FMWCNT nanofluid, the model again shows strong agreement with experimental data, with deviations mostly within $\pm 10\%$. This consistency further validates the model for different types of nanofluids. In Fig. (4.47b) the comparison with literature data (AKRAM *et al.*, 2022) shows that the model predictions align well, with deviations within $\pm 20\%$. This comparison demonstrates that the proposed model is reliable for predicting convective heat transfer coefficients across different studies and conditions.

Fig. (4.48a) illustrate the model's predictions for graphene nanofluid also align closely with experimental results, with deviations largely within $\pm 10\%$. This consistency across different nanofluids (MWCNT, FMWCNT, and graphene) emphasizes the model's generalization. In Fig. (4.48b), the model's predictions for graphene nanofluid are within $\pm 30\%$ of the literature data (MOHAMMAD *et al.*, 2022), which is slightly higher than for MWCNT and FMWCNT. However, this is still an acceptable range, indicating that the model is robust even for different types of nanofluids with varying thermal properties.

4.7.2 Heat transfer by convection in turbulent regime for nanofluid flowing under expansion

Few researchers have studied turbulent axisymmetric sudden enlargement flows and observed reasonable agreement in the location and value of the maximum local Nusselt number, despite some uncertainty in the corner region (GEDIK *et al.*, 2015; KANNA *et al.*, 2015; MONTAZER *et al.*, 2018; TOGUN *et al.*, 2016a; WONG *et al.*, 2015). This uncertainty is largely due to the high conduction corrections needed for wall heat flux and the significant axial thermal conduction in the metal pipe walls (MONTAZER *et al.*, 2020a). Fig. (4.49) presents the comparison between the experimentally measured convective heat transfer coefficients for nanofluids samples in fully developed turbulent flow with expansion, and those predicted by the Gnielinski correlation (Eq. (3.16)). The average deviations between the experimental data and the predictions from the classical model are detailed in Table 4.9.

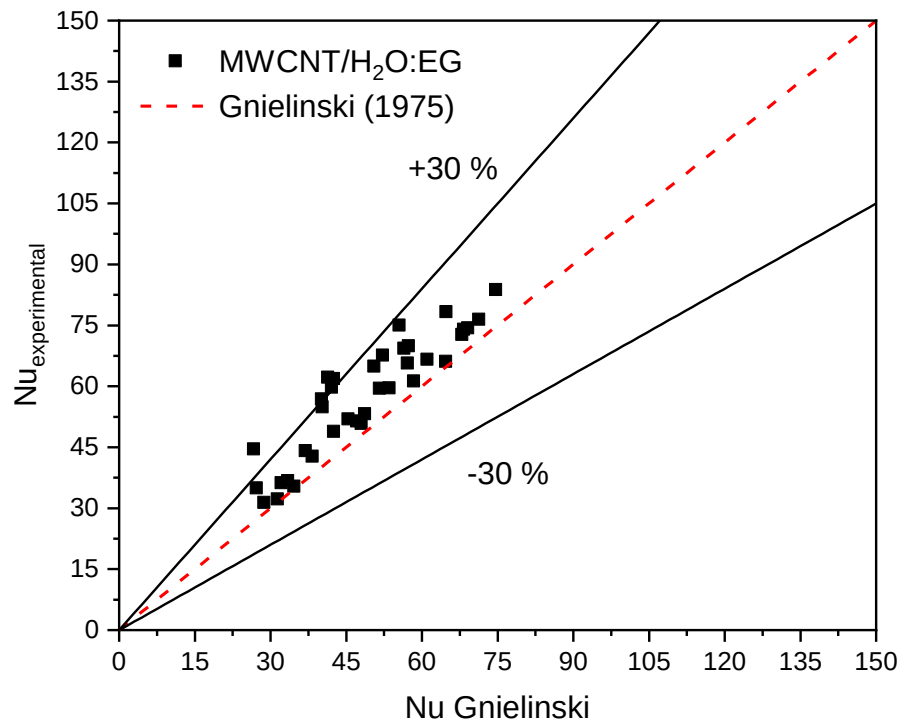
Fig. (4.46) shows that the experimental heat transfer data deviated by more than $\pm 30\%$ from the classical model. As with the straight pipe case, the average deviations between the experimental heat transfer coefficients and the Gnielinski correlation, detailed in Table 4.9, highlight the need for a mathematical correlation that properly aligns with the experimental results for the nanofluids samples in fully turbulent flow through a sudden expansion pipe.

Similar to the straight pipe case, the first step in defining a convective heat transfer model is to establish the relationship between the heat transfer process and the flow field, primarily characterized by the Reynolds number, along with the heat and momentum transfer rates governed by the Prandtl number (Pr). As with the analysis of nanofluid flow in a straight pipe, an exponential correlation for these parameters, as presented in Eq. (4.4), can be effectively used to correlate the experimental heat transfer data. The constants for expansion pipe are presented in Table 10.

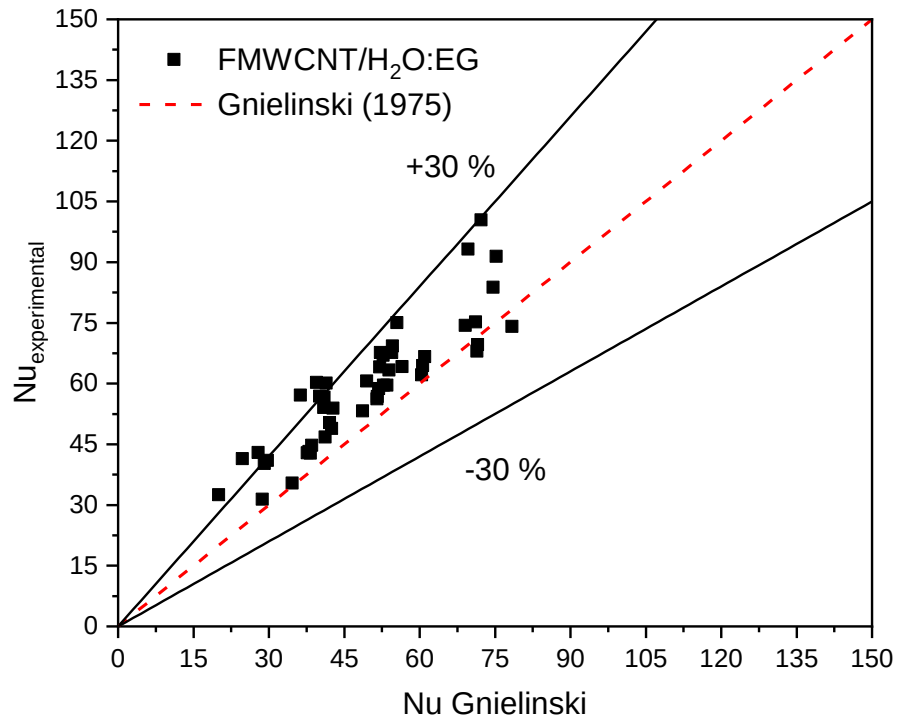
Table 4.9 – Average deviation of experimental data and Gnielinski's model (1975).

Nanofluid	Average deviation presented with Gnielinski's correlation	
	$\phi = 0.005 \%$	$\phi = 0.01 \%$
MWCNT	16.21 %	15.47 %
FMWCNT	11.97 %	13.47 %
Industrial graphene	17.89 %	39.43 %

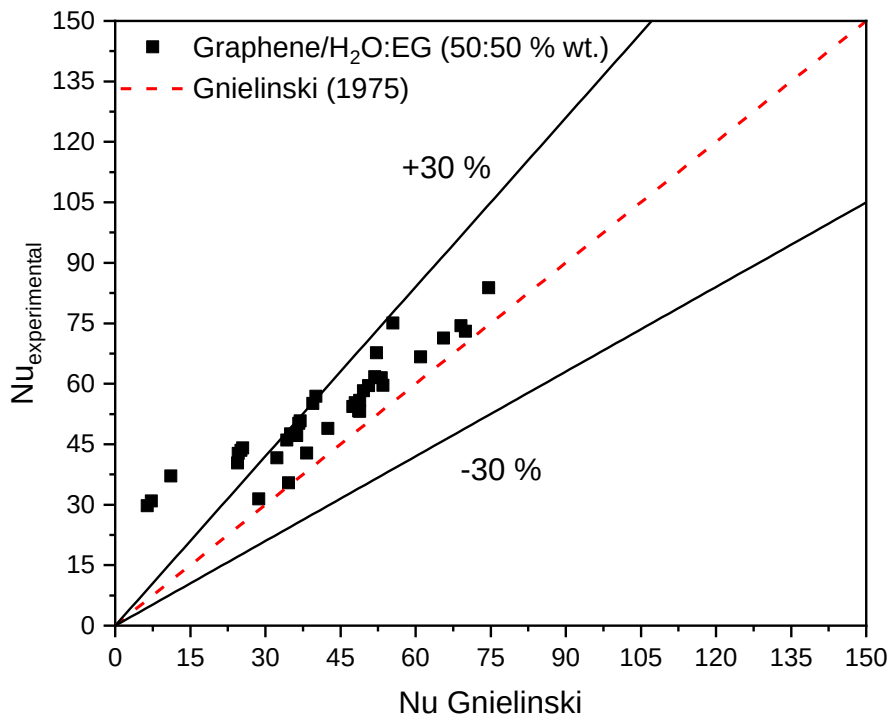
Source: Author's own.



(a)



(b)



(c)

Figure 4.49 – Comparison between the experimental convective heat transfer coefficient and Gnielinski's correlation for nanofluid flowing under expansion. (a) MWCNT. (b) FMWCNT. (c) Industrial graphene. Source: Author's own.

Table 4.11 summarizes the average deviations between the proposed model and the experimental results for nanofluids based on (H₂O:EG 50:50 % wt.). The data, along with Figs. (4.50) to (4.52), illustrate a reasonable agreement between the experimental findings and the proposed model for heat transfer in nanofluids under fully developed turbulent flow with sudden expansion.

Table 4.10 – Parameters of correlations for the nanofluid flowing under expansion.

Constant	MWCNT	FMWCNT	Graphene
C_{nf}	-158.7	102.1	180400
m	1.055	1.05	1.053
X_{nf}	3.418	3.734	3.069

Source: Author's own.

Table 4.11 – Average deviation of experimental data and Gnielinski's model (1975).

Nanofluid	Average deviation presented with proposed correlation	
	$\varphi = 0.005 \%$	$\varphi = 0.01 \%$
MWCNT	2.65 %	2.03 %
FMWCNT	2.97 %	3.68 %
Industrial graphene	4.73 %	10.13 %

Source: Author's own.

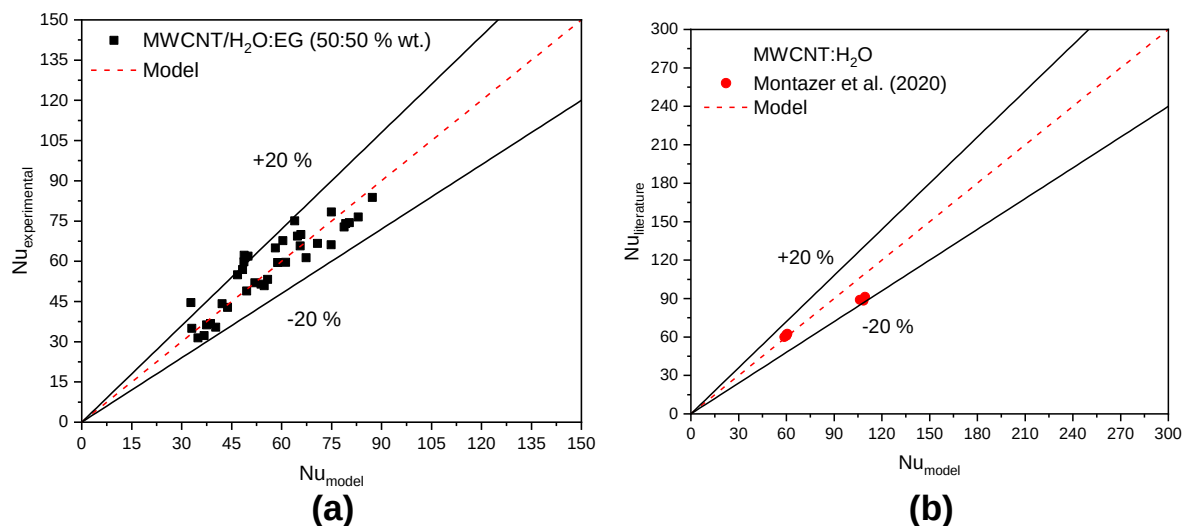


Figure 4.50 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for MWCNT nanofluid samples. (a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.

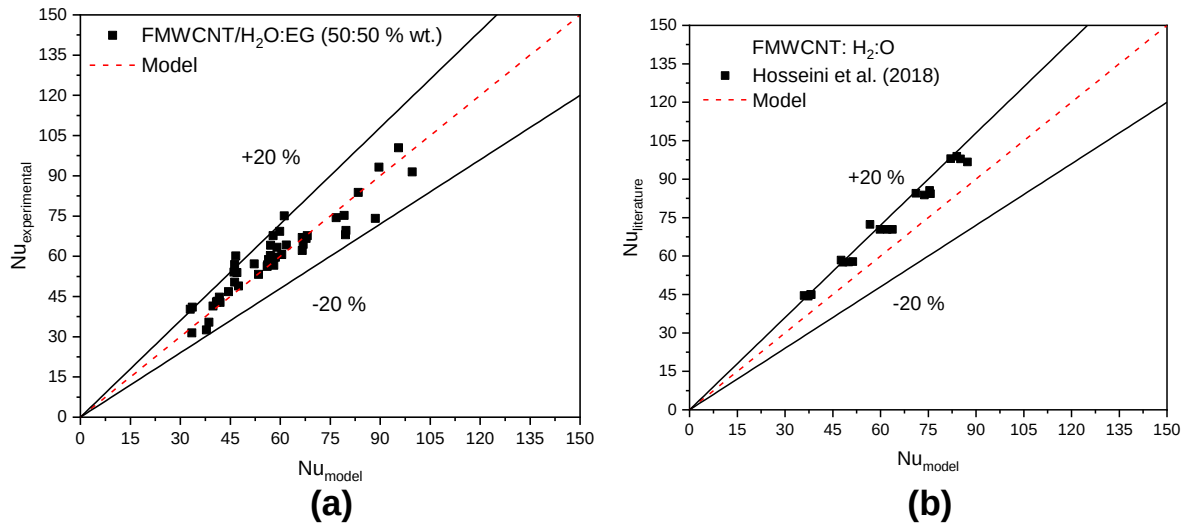


Figure 4.51 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for FMWCNT nanofluid samples. (a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.

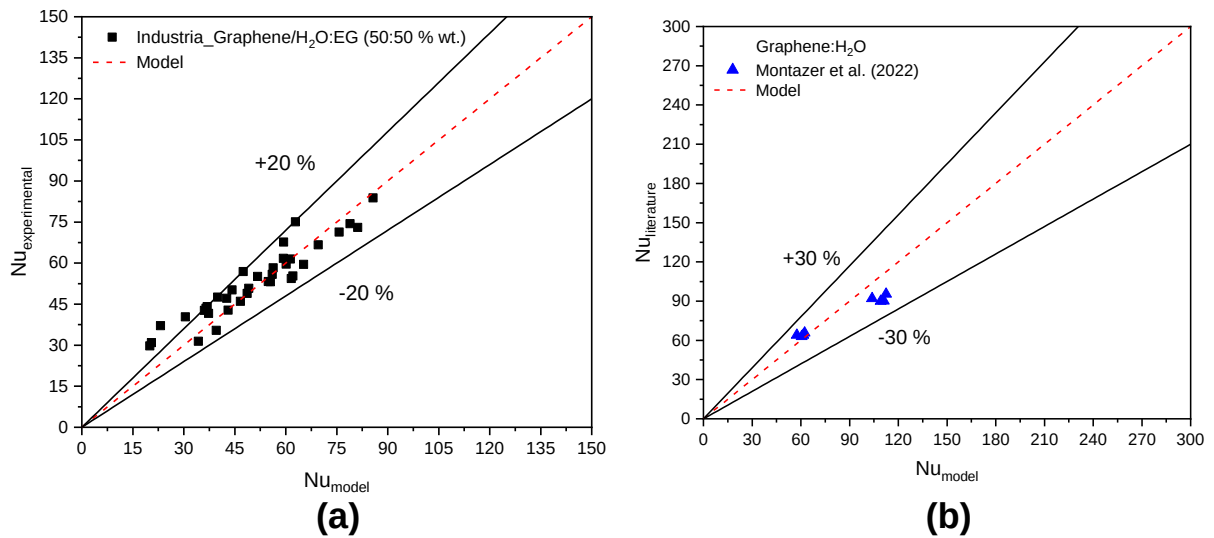


Figure 4.52 – Comparison between the experimental convective heat transfer coefficient and the proposed correlation in turbulent conditions for Industrial graphene nanofluid samples. (a) $Nu_{model} \times Nu_{experimental}$. (b) $Nu_{model} \times Nu_{literature}$. Source: Author's own.

Fig. (4.50a) compares the experimental convective heat transfer coefficient with the proposed model under turbulent conditions for MWCNT nanofluid samples. The results show that the model aligns closely with the experimental data, with deviations within $\pm 10\%$, indicating that the model effectively predicts the heat transfer behavior for this nanofluid in the

given conditions. Fig. (4.50b) the model with existing literature data (MONTAZER *et al.*, 2020a), further supporting its validity. The model's predictions remain within the $\pm 20\%$ deviation range compared to the literature, which is an acceptable range for engineering models.

Fig. (4.51a) provides a similar analysis for FMWCNT nanofluid samples. The experimental data and the proposed model exhibit a strong correlation, with deviations mostly within the $\pm 10\%$ range. The accuracy of the model in predicting the experimental heat transfer coefficients indicates its applicability to different nanofluid types. The close agreement suggests that the model parameters, including constants like C_x , m , and x_{nf} , are appropriate for FMWCNT samples. In Fig (4.51b) the model is also compared with data from the literature (HOSSEINI *et al.*, 2018), showing deviations within $\pm 20\%$. This reinforces the robustness of the proposed model across different studies and experimental setups.

Fig. (4.52a) illustrate for the industrial graphene a comparison between the experimental data and the proposed model. The alignment is generally within $\pm 10\%$, though there is a slightly higher deviation compared to MWCNT and FMWCNT samples, particularly at higher Reynolds numbers. When compared to literature data (MONTAZER *et al.*, 2020a), the model shows deviations up to $\pm 30\%$, which, while higher, are still within a reasonable range considering the complexities of graphene nanofluids, Fig. (4.52b).

4.7.3 Heat transfer by convection in turbulent regime for nanofluid flowing under contraction

The results for heat transfer presented in **sec. 4.3** indicate that the Reynolds number and nanoparticle concentration, substantially affects the heat transfer coefficient. Furthermore, the constriction of the channel passage induces the formation of two recirculation regions, resulting in an enhanced local heat transfer coefficient as observed by (ABDULRAZZAQ *et al.*, 2020b; SAFAEI *et al.*, 2014; SONG *et al.*, 2023; TOGUN *et al.*, 2014a). These recirculation zones significantly increase the heat transfer coefficient right after the contraction.

As reported by the straight pipe case and the expansion case, the Nusselt number for a specific geometry can be formulated as a function of the Reynolds number (Re), Prandtl number (Pr), and the spatial coordinate ' x '. This formulation is versatile, allowing its application to various fluids with differing flow velocities over geometries of similar shape but varying lengths. The importance of this relationship lies in its ability to define the Nusselt number exclusively in terms of the Reynolds and Prandtl numbers for a given geometry. A notable example of such a relationship is the Chilton-Colburn analogy, which is derived from the similarity between momentum and heat transfer in boundary layers (BERGMAN *et al.*, 2011).

Fig. (4.53) and Fig. (4.54) shows the correlation for CR = 1.4 and CR = 1.9 respectively using Chilton-Colburn analogy, Tables 4.12 and 4.13 shows the correlations and the parameters used in these equations. The j -factor method developed by (CHILTON and COLBURN, 1934) for representing data on heat transfer between a turbulent fluid and the wall of a pipe, is a quantitative relation that exist between heat transfer by conduction and convection and in momentum transfer as can be seen in Eq. (4.7).

$$j = St \cdot Pr^{2/3} = (Nu \cdot Pr^{-1/3})/Re \quad (4.7)$$

where the j is a correlating parameter to include the effect of Prandtl number based on the then available data for turbulent flow. Based on presently available experimental data, however, the j factor is clearly dependent on Pr for fully developed turbulent flow and for fully developed laminar flow, but not for ideal developing laminar flows.

The dimensionless experimental heat transfer characteristics are presented in terms of the Colburn factor j , versus Reynolds number Re , and the theoretical characteristics in terms of Nusselt number Nu versus Re as can be seen in Fig (4.53) for CR = 1.4 and CR = 1.9.

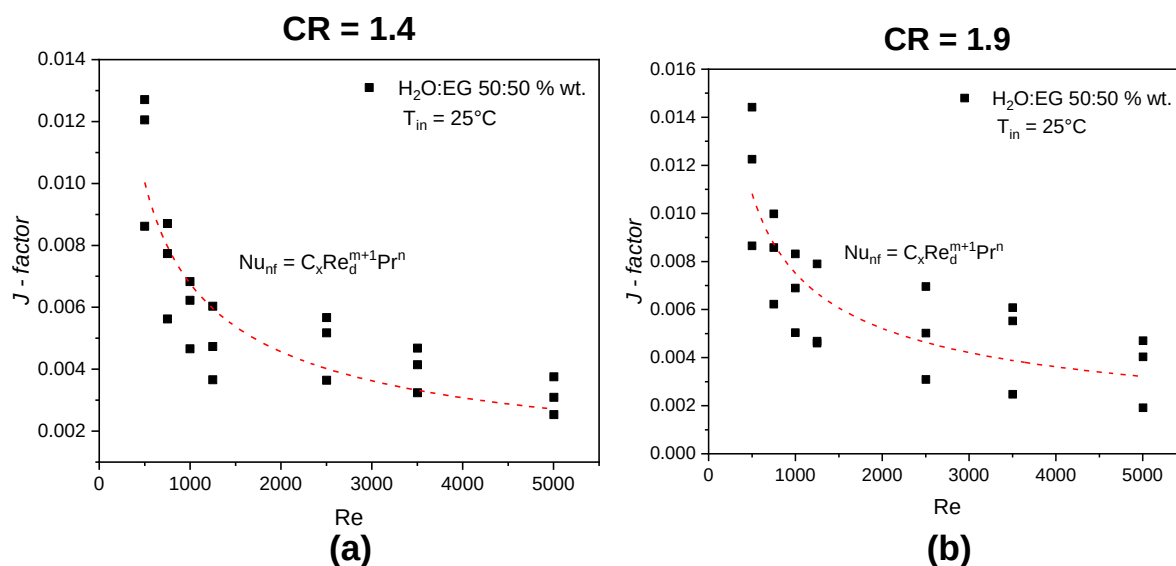


Figure 4.53 – Colburn heat transfer factor j versus Reynolds, Re number for turbulent flow of base fluid (H_2O -EG 50:50 % wt.) under contraction. (a) CR = 1.4. (b) CR = 1.9. Source: Author's own.

The j-factor is adjusted for both contraction ratios (CR = 1.4 and CR = 1.9), allowing for the development of a correlation model. This model captures the dependence of the Nusselt number (Nu) on the Reynolds number, Prandtl number (Pr), and nanoparticle concentration, effectively predicting the heat transfer performance. Fig. (4.54) and Fig. (4.55) shows the correlation for CR = 1.4 and CR = 1.9 respectively using Chilton-Colburn analogy, Tables 4.12 and 4.13 shows the correlations and the parameters used in these equations. The correlations model was derived using the curve-fitting method via the Marquardt-Levenberg algorithm, as proposed by Marquardt (1963) and implemented in MATLAB. This approach, similar to the one used for straight pipe and sudden expansion cases, allows for the determination of the coefficients of the independent variables such as C_{nf} , m and x_{nf} that yield the optimal fit by minimizing the sum of the squared differences between the experimental data and the predicted values. The deviations between the experimental data and the model are acceptable, indicating that the proposed correlation models are and reliable for predicting heat transfer in the studied scenarios.

Table 4.12 – Correlation models for geometry investigated.

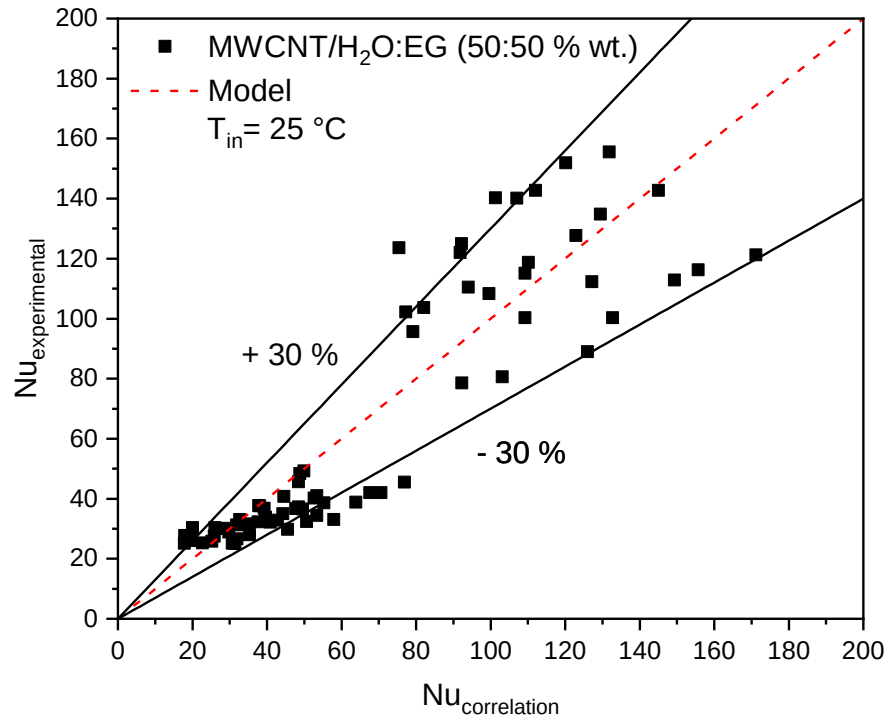
Geometry	Model	Correlation
CR = 1.4	$Nu_{nf} = C_x \cdot Re_d^{m+1} \cdot Pr^n,$ $C_x = C \cdot (1 + C_{nf} \cdot \varphi^{x_{nf}}), n = 1/3$	$Nu_{nf} = 0.401 \cdot (1 + C_{nf} \cdot \varphi^{x_{nf}}) \cdot Re_d^{m+1} \cdot Pr^n$ $0.005 \% \leq \varphi \leq 0.01 \%$ $T_{in} = 25 \text{ } ^\circ\text{C}$
CR = 1.9	$Nu_{nf} = C_x \cdot Re_d^{m+1} \cdot Pr^n,$ $C_x = C \cdot (1 + C_{nf} \cdot \varphi^{x_{nf}}), n = 0.6$	$Nu_{nf} = 0.4587 \cdot (1 + C_{nf} \cdot \varphi^{x_{nf}}) \cdot Re_d^{m+1} \cdot Pr^n$ $0.005 \% \leq \varphi \leq 0.01 \%$ $T_{in} = 25 \text{ } ^\circ\text{C}$

Source: Author's own.

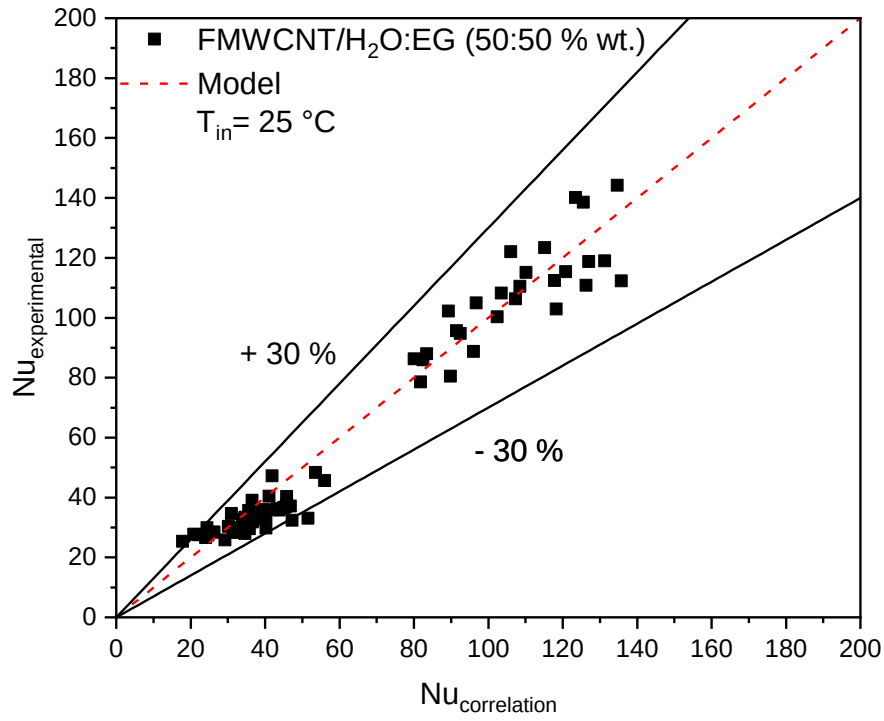
Table 4.13 – Parameters of correlations.

Parameters	CR = 1.4			CR = 1.9		
	MWCNT	FMWCNT	Graphene	MWCNT	FMWCNT	Graphene
C_{nf}	0.6815	0.4243	2.095	8.401	-67.46	151.1
m	0.5801	0.5711	0.5406	0.5442	0.5405	0.5375
x_{nf}	0.08845	0.03033	4.173	27.51	99.79	6.408

Source: Author's own.



(a)



(b)

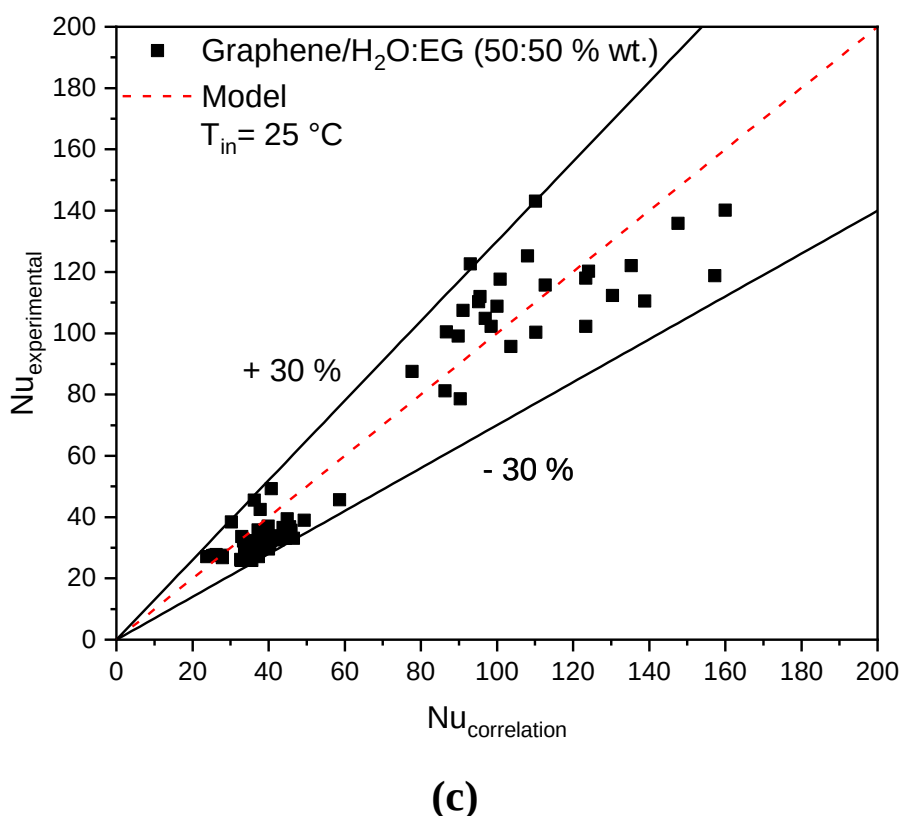
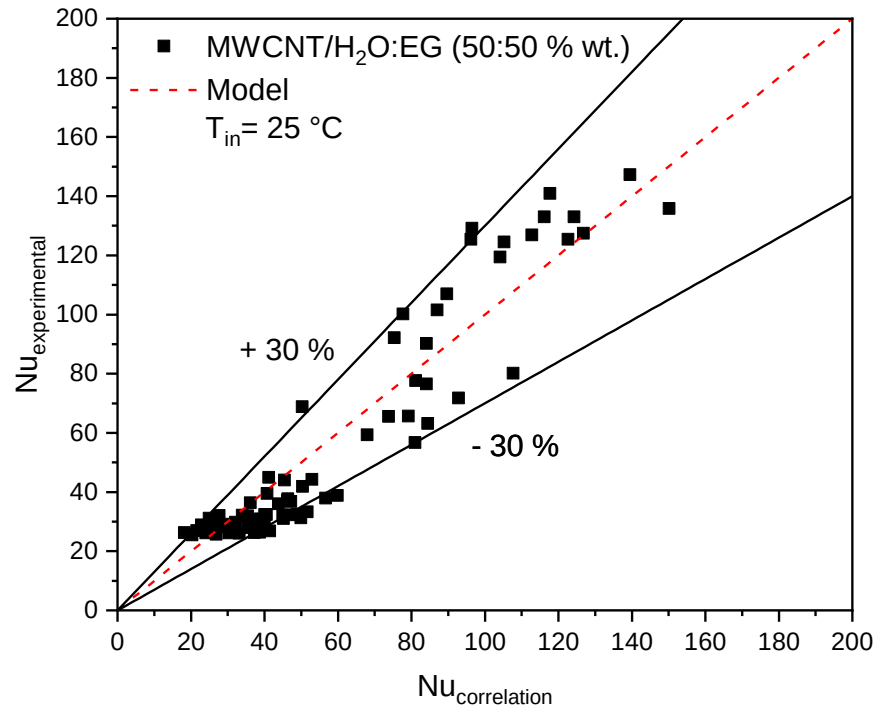


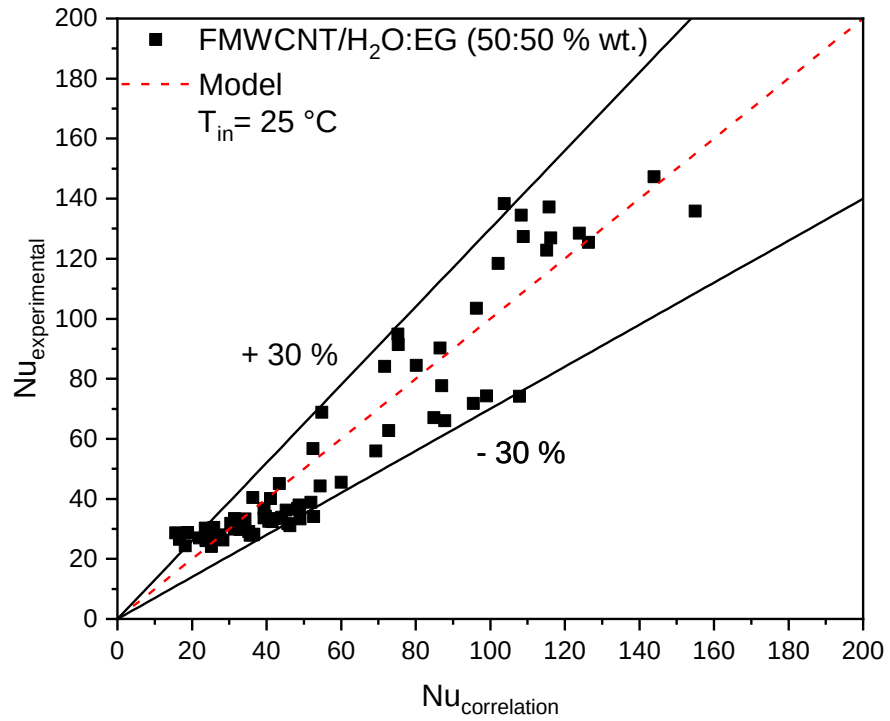
Figure 4.54 – Correlation for CR = 1.4. (a) MWCNT. (b) FMWCNT. (c) Graphene. Source: Author's own.

Fig. (4.54) and Fig. (4.55) illustrates the dependence of the Nusselt number on the Reynolds number for nanofluids containing MWCNT, FMWCNT, and graphene. Both MWCNT and FMWCNT show a significant increase in the Nusselt number with increasing Reynolds number, indicating enhanced convective heat transfer. However, FMWCNT tends to exhibit slightly higher Nusselt numbers than MWCNT due to improved dispersion and interaction with the base fluid. The nanofluid with graphene shows the highest Nusselt numbers across all Reynolds numbers, outperforming both MWCNT and FMWCNT. This superior performance is attributed to the high thermal conductivity and surface area of graphene, which enhances energy transfer within the fluid.

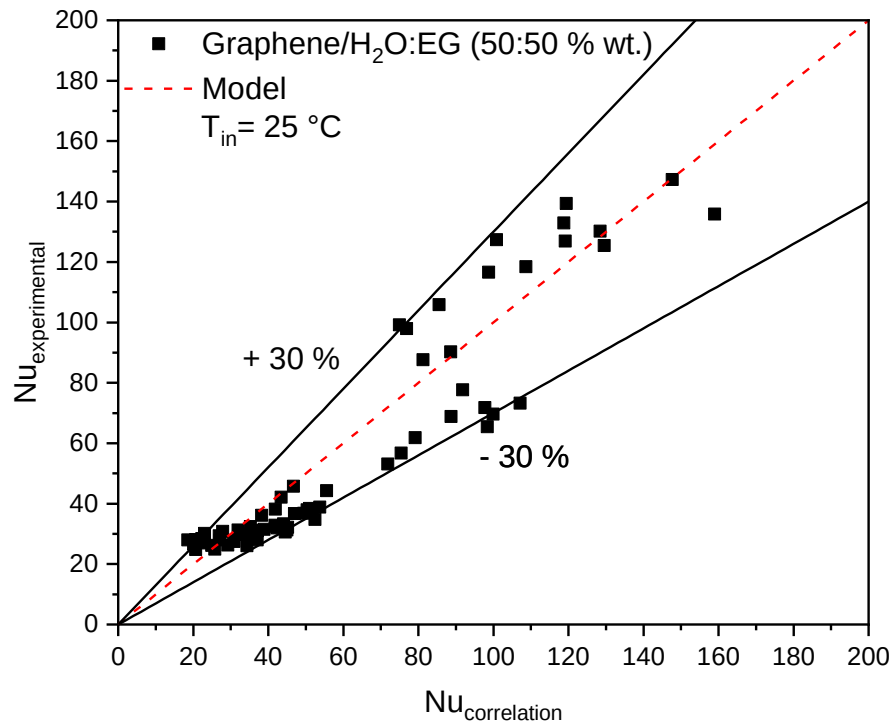
The proposed models effectively predict the heat transfer behavior across different contraction ratios, with acceptable deviations observed between the experimental data and the model predictions. This analysis underscores the potential of graphene as an advanced material for enhancing heat transfer in nanofluid applications.



(a)



(b)



(c)

Figure 4.55 – Correlation for $CR = 1.9$. (a) MWCNT. (b) FMWCNT. (c) Graphene. Source: Author's own.

CHAPTER V

CONCLUSIONS

This thesis explores the thermohydraulic performance of nanofluids flowing through closed conduits with sudden geometry change, specifically those containing multi-walled carbon nanotubes (MWCNT), functionalized multi-walled carbon nanotubes (FMWCNT), and graphene, dispersed in a mixture of water – ethylene glycol 50:50 % in mass concentration (H₂O - EG 50:50 % wt.). The nanofluids were examined in a horizontal tube system with sudden expansion or contraction under both laminar and turbulent flow regimes. The research was conducted through an experimental investigation evaluating the effects of nanoparticle concentration, flow regime, heat fluxes and temperature on heat transfer and pressure drop within these configurations.

The experimental setup was initially modified to fit the specific requirements necessary for conducting the tests. As a result, a large amount of experimental data was obtained, making it possible to carry out various analyses in terms of heat transfer and pressure drop. Consequently, the objectives of this study were successfully achieved. The main conclusions of this research are presented below, along with suggestions and recommendations for future work.

5.1 Final conclusions

The experimental investigation into the thermohydraulic performance of nanofluids containing multi-walled carbon nanotubes (MWCNT), functionalized multi-walled carbon nanotubes (FMWCNT), and graphene provided comprehensive insights into how these nanofluids behave under various flow conditions and geometries.

- **Enhancement of heat transfer:** The addition of nanoparticles significantly enhanced the heat transfer coefficient of the base fluid across all tested conditions. Among the nanofluids, FMWCNT nanofluids demonstrated the highest heat transfer improvements, with increases of up to 20.44 % at a nanoparticle concentration of 0.01 % by weight. Graphene nanofluids also showed substantial improvements, with increases of up to 17.85 %, while MWCNT nanofluids exhibited the least enhancement at 7.29 %.
- **Impact of Reynolds number:** As the Reynolds number increased, the heat transfer coefficient also increased, indicating that higher flow rates promote better mixing and turbulence within the fluid, thereby enhancing the convective heat transfer. The most significant gains were observed in the turbulent flow regime, where the combination of high Reynolds numbers and optimal nanoparticle concentrations led to substantial improvements in heat transfer efficiency.
- **Influence of nanoparticle concentration:** Nanoparticle concentration plays a vital role in determining the extent of heat transfer enhancement. While higher concentrations generally led to better heat transfer, there were diminishing returns beyond a certain point. For example, increasing the concentration from 0.005 % to 0.01 % by weight resulted in significant improvements, but further increases to 0.05 % did not yield proportional gains. This suggests that there is an optimal concentration range where the benefits of nanoparticle addition are maximized without introducing excessive viscosity or potential issues with particle agglomeration.
- **Effect of heat flux:** Interestingly, the increase in heat flux (from 5 kW/m² to 12 kW/m²) did not have a significant impact on the heat transfer coefficient, indicating that the thermohydraulic performance of the nanofluids is more strongly influenced by flow conditions (such as Reynolds number and nanoparticle concentration) than by the applied heat flux. However, heat flux did influence the pressure drop across the system, particularly in configurations with sudden expansions or contractions. Higher heat fluxes led to increased thermal gradients, which could contribute to greater pressure losses, especially in geometries with abrupt changes.
- **Pressure drop effects:** Introducing nanoparticles increased the pressure drop within the system, especially at higher concentrations and in configurations with sudden expansions or contractions. This is likely due to the increased viscosity and density of the nanofluids, as well as the complex flow dynamics introduced by the presence of nanoparticles. The pressure drop was more pronounced in cases where the flow

transitioned from laminar to turbulent regimes, suggesting that while nanofluids can enhance heat transfer, they may also require more energy to pump, depending on the specific system configuration.

- **Geometric effects:** The geometric configuration of the flow path, such as contraction and expansion ratios, significantly influences both heat transfer and pressure drop. Sudden expansion or contraction create recirculation zones that enhance mixing and heat transfer, but also increase pressure losses. The contraction ratio (CR) and the expansion ratio (ER) is a critical parameter that must be carefully considered when designing systems that utilize nanofluids, as it directly affects the fluid dynamics and, thus, the overall thermal performance.
- **Deviation from traditional correlations:** The research highlighted that traditional correlations for heat transfer and pressure drop, which are typically used for single-phase fluids, do not fully capture the behavior of nanofluids, particularly in systems with sudden changes in geometry. The presence of nanoparticles alters the flow characteristics in ways that are not accounted for in these conventional models, leading to deviations in predicted versus observed performance. This finding underscores the necessity for developing new correlations and models specifically adapted to nanofluids, which consider the unique interactions between nanoparticles, base fluids, and the flow environment.

In summary, this study provides significant empirical data that enhance the understanding of thermohydraulic performance of nanofluids in complex flow environments. The findings support further research and development efforts focused on optimizing nanofluid formulations and system designs to improve thermal performance in engineering applications.

5.2 Recommendations for future work

- **Broader range of nanoparticles:** Future research should explore a wider variety of nanoparticle types and concentrations to better understand their effects on thermohydraulic performance. This could include the use of metal oxides, hybrid nanoparticles, or other carbon-based materials.
- **Development of new models:** Given the observed deviations from traditional correlations, there is a need for more sophisticated models that can accurately predict the behavior of nanofluids under varying flow conditions and geometries. These models

should account for the complex interactions between nanoparticles, base fluids, and flow conditions.

- **Long – term stability studies:** Investigating the long-term stability of nanofluids, particularly under operational conditions, is crucial. Future work should focus on the potential degradation of nanofluids over time, especially when exposed to high temperatures and flow rates.
- **Effect of base fluids and surfactants:** The choice of base fluid and surfactants significantly impacts the stability and performance of nanofluids. Future studies should examine the effects of different base fluids and surfactants on thermohydraulic performance to optimize nanofluid formulations for specific applications.
- **Different geometric configuration:** Expanding the analysis to include various geometric configurations beyond sudden expansions and contractions would provide a more comprehensive understanding of nanofluid behavior. This could involve investigating different channel shapes, sizes, and boundary conditions.
- **Operational and Application-Specific Studies:** Finally, applying the findings of this research to real-world applications, such as in automotive radiators, electronic cooling systems, or industrial heat exchangers, could validate the experimental results and models, leading to the optimization of nanofluid-based thermal management systems for specific industries.

REFERENCES

ABD. RAHIM ABU TALIB; SADEQ SALMAN; MUHAMMAD FITRI MOHD ZULKEPLE; ALI KAREEM HILO. Experimental Investigation of Nanofluid Turbulent Flow Over Microscale Backward-Facing Step. **Journal of Advanced Research in Fluid Mechanics and Thermal Sciences**, v. 99, n. 2, p. 119–134, 2022. Disponível em: <https://doi.org/10.37934/arfmts.99.2.119134>

ABDELALL, F. F.; HAHN, G.; GHIAASIAAN, S. M.; ABDEL-KHALIK, S. I.; JETER, S. S.; YODA, M.; SADOWSKI, D. L. Pressure drop caused by abrupt flow area changes in small channels. **Experimental Thermal and Fluid Science**, v. 29, n. 4, p. 425–434, 2005. Disponível em: <https://doi.org/10.1016/j.expthermflusci.2004.05.001>

ABDELRAZEK, A. H.; KAZI, S. N.; ALAWI, O. A.; YUSOFF, N.; OON, C. S.; ALI, H. M. Heat transfer and pressure drop investigation through pipe with different shapes using different types of nanofluids. **Journal of Thermal Analysis and Calorimetry**, v. 139, n. 3, p. 1637–1653, 2020. Disponível em: <https://doi.org/10.1007/s10973-019-08562-5>

ABDRABBUH, O. A.; ABDELRAZEK, A. H.; KAZI, S. N.; ZUBIR, M. N. M. Nanofluids thermal performance in the horizontal annular passages: a recent comprehensive review. **Journal of Thermal Analysis and Calorimetry**, v. 147, n. 21, p. 11633–11660, 2022. Disponível em: <https://doi.org/10.1007/s10973-022-11389-2>

ABDULRAZZAQ, T.; TOGUN, H.; ALSULAMI, H.; GOODARZI, M.; SAFAEI, M. Heat Transfer Improvement in a Double Backward-Facing Expanding Channel Using Different Working Fluids. **Symmetry**, v. 12, n. 7, p. 1088, 2020 a. Disponível em: <https://doi.org/10.3390/sym12071088>

ABDULRAZZAQ, T.; TOGUN, H.; GOODARZI, M.; KAZI, S. N.; ARIFFIN, M. K. A.; ADAM, N. M.; HOOMAN, K. Turbulent heat transfer and nanofluid flow in an annular cylinder with sudden reduction. **Journal of Thermal Analysis and Calorimetry**, v. 141, n. 1, p. 373–385, 2020 b. Disponível em: <https://doi.org/10.1007/s10973-020-09538-6>

ABDULRAZZAQ, T.; TOGUN, H.; REZA, S.; KAZI, S.; ARIFFIN, M.; ADAM, N. Effect of flow separation of TiO₂ nanofluid on heat transfer in the annular space of two concentric cylinders. **Thermal Science**, v. 24, n. 2 Part A, p. 1007–1018, 2020 c. Disponível em: <https://doi.org/10.2298/TSCI180709321A>

ABDULRAZZAQ, T.; TOGUN, H.; SAFAEI, M. R.; KAZI, S. N.; ARIFFIN, M. K. A. B. M.; ADAM, N. M. Effect of flow separation of TiO₂ nanofluid on heat transfer in the annular space of two concentric cylinders. **Thermal Science**, v. 24, n. 2PartA, p. 1007–1018, 2020 d. Disponível em: <https://doi.org/10.2298/TSCI180709321A>

ABU TALIB, Abd. R.; SALMAN, S. Heat transfer and fluid flow analysis over the microscale backwardfacing step using β Ga₂O₃ nanoparticles. **Experimental Heat Transfer**, v. 36, n. 3, p. 358–375, 2023. Disponível em: <https://doi.org/10.1080/08916152.2022.2039328>

ABU-NADA, E. Application of nanofluids for heat transfer enhancement of separated flows encountered in a backward facing step. **International Journal of Heat and Fluid Flow**, v. 29, n. 1, p. 242–249, 2008. Disponível em: <https://doi.org/10.1016/j.ijheatfluidflow.2007.07.001>

ABU-NADA, E. Effects of variable viscosity and thermal conductivity of Al₂O₃–water nanofluid on heat transfer enhancement in natural convection. **International Journal of Heat and Fluid Flow**, v. 30, n. 4, p. 679–690, 2009. Disponível em: <https://doi.org/10.1016/j.ijheatfluidflow.2009.02.003>

ACAR, B. Laminar forced convection of various nanofluids in sudden expansion channels under constant heat flux: A CFD study. **International Journal of Applied Mechanics**, v. 11, n. 5, 2019 a. Disponível em: <https://doi.org/10.1142/S1758825119500492>

ACAR, B. Laminar Forced Convection of Various Nanofluids in Sudden Expansion Channels Under Constant Heat Flux: A CFD Study. **International Journal of Applied Mechanics**, v. 11, n. 05, p. 1950049, 2019 b. Disponível em: <https://doi.org/10.1142/S1758825119500492>

AFSHARI, F.; MANAY, E.; RAHIMPOUR, S.; SAHIN, B.; MURATÇOBANOGLU, B.; TEIMURI-MOFRAD, R. A REVIEW STUDY ON FACTORS AFFECTING THE STABILITY OF NANOFLUIDS. **Heat Transfer Research**, v. 53, n. 18, p. 77–91, 2022. Disponível em: <https://doi.org/10.1615/HeatTransRes.2022041979>

AHMAD, W.; ULLAH, Z.; SONIL, N. I.; KHAN, K. Introduction, production, characterization and applications of defects in graphene. **Journal of Materials Science: Materials in Electronics**, v. 32, n. 15, p. 19991–20030, 2021. Disponível em: <https://doi.org/10.1007/s10854-021-06575-1>

AKRAM, N.; HOSSEINI, M.; SADRI, R.; KAZI, S. N.; KASAEIAN, A.; YARMAND, H.; HOOMAN, K.; AHMAD, R. A facile, green fabrication of aqueous nanofluids containing hydrophilic functionalized carbon nanotubes toward improving heat transfer in a closed horizontal flow passage. **Powder Technology**, v. 404, p. 117451, 2022. Disponível em: <https://doi.org/10.1016/j.powtec.2022.117451>

AL-ASWADI, A. A.; MOHAMMED, H. A.; SHUAIB, N. H.; CAMPO, A. Laminar forced convection flow over a backward facing step using nanofluids. **International Communications in Heat and Mass Transfer**, v. 37, n. 8, p. 950–957, 2010. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2010.06.007>

ALAWI, O. A.; SIDIK, N. A. C.; XIAN, H. W.; KEAN, T. H.; KAZI, S. N. Thermal conductivity and viscosity models of metallic oxides nanofluids. **International Journal of Heat and Mass Transfer**, v. 116, p. 1314–1325, 2018. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.133>

AL-DAMOOK, A.; AZZAWI, I. D. J. Optimal hydro-thermal characteristics of a porous annular elliptic pipe using response surface method. **International Communications in Heat and Mass Transfer**, v. 128, p. 105632, 2021. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2021.105632>

AL-GAILANI, A. Air flow through an axisymmetric sudden expansion of confined co-axial circular duct: Numerical study. **1st International Scientific Conference of Engineering Sciences - 3rd Scientific Conference of Engineering Science, ISCES 2018 - Proceedings**, v. 2018- Janua, p. 146–151, 2018. Disponível em: <https://doi.org/10.1109/ISCES.2018.8340544>

ALHAKEEM, M. R. H. Enhancing Thermal Conductivity and Heat Transfer using Graphene Nanofluid. **International Journal of Multidisciplinary Sciences and Arts**, v. 1, n. 1, p. 95–103, 2022. Disponível em: <https://doi.org/10.47709/ijmdsa.v1i1.1710>

ALHARBI, S. O.; KHALIFA, H. A. E.-W.; GUL, T.; ALHARBI, R.; ALBURAIKAN, A.; BARIQ, A. The use of neural computational analysis for drug delivery applications results in hybrid nanofluid flow between the uniform gap of two concentric tubes. **Discover Applied Sciences**, v. 6, n. 4, p. 200, 2024. Disponível em: <https://doi.org/10.1007/s42452-024-05742-3>

ALI, A. R. I.; SALAM, B. A review on nanofluid: preparation, stability, thermophysical properties, heat transfer characteristics and application. **SN Applied Sciences**, v. 2, n. 10, p. 1636, 2020 a. Disponível em: <https://doi.org/10.1007/s42452-020-03427-1>

ALI, A. R. I.; SALAM, B. A review on nanofluid: preparation, stability, thermophysical properties, heat transfer characteristics and application. **SN Applied Sciences**, v. 2, n. 10, p. 1636, 2020 b. Disponível em: <https://doi.org/10.1007/s42452-020-03427-1>

ALI, N.; TEIXEIRA, J. A.; ADDALI, A. A Review on Nanofluids: Fabrication, Stability, and Thermophysical Properties. **Journal of Nanomaterials**, v. 2018, 2018. Disponível em: <https://doi.org/10.1155/2018/6978130>

ALIZADEH, R.; DORFAKI, V.; AMERI, A.; VALIZADEH ARDALAN, M.; JAVIDI SARAFAAN, M. Heat transfer and pressure drop in a sinus blowing of copper oxide- water non-Newtonian nanofluid in a sudden expansion process in the presence of variable magnetic field: a numerical solution. **Energy Sources, Part A: Recovery, Utilization and Environmental Effects**, v. 00, n. 00, p. 1–24, 2020 a. Disponível em: <https://doi.org/10.1080/15567036.2020.1817195>

ALIZADEH, R.; DORFAKI, V.; AMERI, A.; VALIZADEH ARDALAN, M.; JAVIDI SARAFAAN, M. Heat transfer and pressure drop in a sinus blowing of copper oxide- water non-Newtonian nanofluid in a sudden expansion process in the presence of variable magnetic field: a numerical solution. **Energy Sources, Part A: Recovery, Utilization, and Environmental Effects**, p. 1–24, 2020 b. Disponível em: <https://doi.org/10.1080/15567036.2020.1817195>

ALKASMOUL, F. S.; ASAKER, M.; ALMOGBEL, A.; ALSUWAILEM, A. Combined effect of thermal and hydraulic performance of different nanofluids on their cooling efficiency in

microchannel heat sink. **Case Studies in Thermal Engineering**, v. 30, p. 101776, 2022. Disponível em: <https://doi.org/10.1016/j.csite.2022.101776>

ALMURTAJI, S.; ALI, N.; TEIXEIRA, J. A.; ADDALI, A. On the Role of Nanofluids in Thermal-hydraulic Performance of Heat Exchangers—A Review. **Nanomaterials**, v. 10, n. 4, p. 734, 2020. Disponível em: <https://doi.org/10.3390/nano10040734>

AL-OBAIDI, A. R. Dynamics simulation in corrugated pipe-based investigations of internal thermo-hydraulic flow and improvement of heat performance under various corrugated geometrical configurations. **Journal of Thermal Analysis and Calorimetry**, 2024. Disponível em: <https://doi.org/10.1007/s10973-024-13467-z>

ALRASHED, A. A. A. A.; AKBARI, O. A.; HEYDARI, A.; TOGHRAIE, D.; ZARRINGHALAM, M.; SHABANI, G. A. S.; SEIFI, A. R.; GOODARZI, M. The numerical modeling of water/FMWCNT nanofluid flow and heat transfer in a backward-facing contracting channel. **Physica B: Condensed Matter**, v. 537, p. 176–183, 2018. Disponível em: <https://doi.org/10.1016/j.physb.2018.02.022>

ALSABERY, A. I.; HAJJAR, A.; SHERMET, M. A.; GHALAMBAZ, M.; HASHIM, I. Impact of particles tracking model of nanofluid on forced convection heat transfer within a wavy horizontal channel. **International Communications in Heat and Mass Transfer**, v. 122, p. 105176, 2021. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2021.105176>

AL-SAMMARRAIE, A. T.; VAFAI, K. Thermal–Hydraulic Performance Analysis of a Convergent Double Pipe Heat Exchanger. **Journal of Heat Transfer**, v. 141, n. 5, 2019. Disponível em: <https://doi.org/10.1115/1.4042487>

AMBREEN, T.; KIM, M. H. Heat transfer and pressure drop correlations of nanofluids: A state of art review. **Renewable and Sustainable Energy Reviews**, v. 91, n. March, p. 564–583, 2018. Disponível em: <https://doi.org/10.1016/j.rser.2018.03.108>

AMIRI, A.; ARZANI, H. K.; KAZI, S. N.; CHEW, B. T.; BADARUDIN, A. Backward-facing step heat transfer of the turbulent regime for functionalized graphene nanoplatelets based water-ethylene glycol nanofluids. **International Journal of Heat and Mass Transfer**, v. 97, p. 538–546, 2016. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2016.02.042>

ANGAYARKANNI, J.; PHILIP, J. Synthesis of Nanoparticles and Nanofluids. *In*: MURSHED, S. M. S. (org.). **Fundamentals and Transport Properties of Nanofluids**. [S. l.]: The Royal Society of Chemistry, 2022. p. 3–40. Disponível em: <https://doi.org/10.1039/9781839166457>

APMANN, K.; FULMER, R.; SOTO, A.; VAFAEI, S. Thermal Conductivity and Viscosity: Review and Optimization of Effects of Nanoparticles. **Materials**, v. 14, n. 5, p. 1291, 2021 a. Disponível em: <https://doi.org/10.3390/ma14051291>

APMANN, K.; FULMER, R.; SOTO, A.; VAFAEI, S. Thermal Conductivity and Viscosity: Review and Optimization of Effects of Nanoparticles. **Materials**, v. 14, n. 5, p. 1291, 2021 b. Disponível em: <https://doi.org/10.3390/ma14051291>

ARSLAN, R.; ÖZDEMİR, V. A.; AKYOL, E.; DALKILIC, A. S.; WONGWISES, S. Thermophysical Properties of Nanofluids. **Current Nanoscience**, v. 17, n. 5, p. 694–727, 2021. Disponível em: <https://doi.org/10.2174/1573413716999201228130519>

ATASHAFROOZ, M.; SHEIKHOLESAMI, M.; SAJJADI, H.; AMIRI DELOUEI, A. Interaction effects of an inclined magnetic field and nanofluid on forced convection heat transfer and flow irreversibility in a duct with an abrupt contraction. **Journal of Magnetism and Magnetic Materials**, v. 478, p. 216–226, 2019. Disponível em: <https://doi.org/10.1016/j.jmmm.2019.01.111>

AVECILLA, F. R. B.; FARAJOLLAHI, A.; ROSTAMI, M.; YADAV, A.; FLORES, J. J. Successive expansion and contraction of tubes (SECT) in a novel design of shell-and-tube heat exchanger: entropy generation analysis. **Journal of the Brazilian Society of Mechanical Sciences and Engineering**, v. 46, n. 5, p. 267, 2024. Disponível em: <https://doi.org/10.1007/s40430-024-04850-w>

AVSEC, J.; OBLAK, M. The calculation of thermal conductivity, viscosity and thermodynamic properties for nanofluids on the basis of statistical nanomechanics. **International Journal of Heat and Mass Transfer**, v. 50, n. 21–22, p. 4331–4341, 2007. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2007.01.064>

AWAIS, M.; SAAD, M.; AYAZ, H.; EHSAN, M. M.; BHUIYAN, A. A. Computational assessment of Nano-particulate (Al₂O₃/Water) utilization for enhancement of heat transfer

with varying straight section lengths in a serpentine tube heat exchanger. **Thermal Science and Engineering Progress**, v. 20, p. 100521, 2020. Disponível em: <https://doi.org/10.1016/j.tsep.2020.100521>

AWAIS, M.; ULLAH, N.; AHMAD, J.; SIKANDAR, F.; EHSAN, M. M.; SALEHIN, S.; BHUIYAN, A. A. Heat transfer and pressure drop performance of Nanofluid: A state-of-the-art review. **International Journal of Thermofluids**, v. 9, p. 100065, 2021. Disponível em: <https://doi.org/10.1016/j.ijft.2021.100065>

AZIZI, Z.; ALAMDARI, A.; MALAYERI, M. R. Thermal performance and friction factor of a cylindrical microchannel heat sink cooled by Cu-water nanofluid. **Applied Thermal Engineering**, v. 99, p. 970–978, 2016. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2016.01.140>

AZIZIFAR, S.; AMERI, M.; BEHROYAN, I. Experimental investigation of the subcooled flow boiling heat transfer of water and nanofluids in a horizontal metal foam tube. **Heat and Mass Transfer**, v. 57, n. 9, p. 1499–1511, 2021. Disponível em: <https://doi.org/10.1007/s00231-021-03042-9>

AZMI, W. H.; HAMID, K. A.; USRI, N. A.; MAMAT, R.; SHARMA, K. V. Heat transfer augmentation of ethylene glycol: water nanofluids and applications — A review. **International Communications in Heat and Mass Transfer**, v. 75, p. 13–23, 2016. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2016.03.018>

AZODINIA, M.; MUDABBIR, M.; KARIMIPOUR, A. Numerical investigation of two-phase Al₂O₃ nanofluid in a microchannel equipped with bump through slip flow. **Engineering Analysis with Boundary Elements**, v. 155, p. 1028–1034, 2023. Disponível em: <https://doi.org/10.1016/j.enganabound.2023.07.019>

BACHA, H. Ben; ULLAH, N.; HAMID, A.; SHAH, N. A. A comprehensive review on nanofluids: Synthesis, cutting-edge applications, and future prospects. **International Journal of Thermofluids**, v. 22, p. 100595, 2024. Disponível em: <https://doi.org/10.1016/j.ijft.2024.100595>

BAI, M.; LIU, J.; HE, J.; LI, Z.; WEI, J.; CHEN, L.; MIAO, J.; LI, C. High efficiency heat transfer and antifriction characteristics of SMWCNTs nanofluids. **Diamond and Related**

Materials, v. 105, p. 107792, 2020. Disponível em: <https://doi.org/10.1016/j.diamond.2020.107792>

BALAGA, R.; KOONA, R.; TUNUGUNTLA, S. Heat transfer enhancement of the f-MWCNT-Fe₂O₃/Water hybrid nanofluid with the combined effect of wire coil with twisted tape and perforated twisted tape. **International Journal of Thermal Sciences**, v. 184, p. 108023, 2023. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2022.108023>

BALAKHRISNA, T.; GHOSH, S.; DAS, G.; DAS, P. K. Oil-water flows through sudden contraction and expansion in a horizontal pipe - Phase distribution and pressure drop. **International Journal of Multiphase Flow**, v. 36, n. 1, p. 13–24, 2010. Disponível em: <https://doi.org/10.1016/j.ijmultiphaseflow.2009.08.007>

BASHIR, A. I.; EVERTS, M.; MEYER, J. P. Influence of inlet contraction ratios on the heat transfer and pressure drop characteristics of single-phase flow in smooth circular tubes in the transitional flow regime. **Experimental Thermal and Fluid Science**, v. 109, n. July, 2019. Disponível em: <https://doi.org/10.1016/j.expthermflusci.2019.109892>

BAUGHN, J. W.; HOFFMAN, M. A.; TAKAHASHI, R. K.; LAUNDER, B. E. Local Heat Transfer Downstream of an Abrupt Expansion in a Circular Channel With Constant Wall Heat Flux. **Journal of Heat Transfer**, v. 106, n. 4, p. 789–796, 1984. Disponível em: <https://doi.org/10.1115/1.3246753>

BEHNAMPOUR, A.; AKBARI, O. A.; SAFAEI, M. R.; GHAVAMI, M.; MARZBAN, A.; SHEIKH SHABANI, G. A.; ZARRINGHALAM, M.; MASHAYEKHI, R. Analysis of heat transfer and nanofluid fluid flow in microchannels with trapezoidal, rectangular and triangular shaped ribs. **Physica E: Low-dimensional Systems and Nanostructures**, v. 91, p. 15–31, 2017. Disponível em: <https://doi.org/10.1016/j.physe.2017.04.006>

BERGMAN, T. L.; LAVINE, A. S.; INCROPERA, F. P.; DEWITT, D. P. **Fundamentals of Heat and Mass Transfer**. 7. ed. Hoboken: John Wiley & Sons, 2011.

BESANJIDEH, M.; HAJABDOLLAHI, M.; GANDJALIKHAN NASSAB, S. A. CFD Based Analysis of Laminar Forced Convection of Nanofluid Separated Flow Under the Presence of Magnetic Field. **Journal of Mechanics**, v. 32, n. 6, p. 777–785, 2016. Disponível em: <https://doi.org/10.1017/jmech.2016.54>

BILAL, S. Analysis about impact of morphological and nanoparticle volume fraction aspects of TiO₂-Cu in enhancement of thermo-physical features of newtonian fluid flowing in a rotating porous channel. **Applied Nanoscience**, v. 13, n. 1, p. 405–419, 2023. Disponível em: <https://doi.org/10.1007/s13204-021-01770-2>

BRICLOT, A.; POPA, C.; HENRY, J. F.; FOHANNON, S. Experimental study of the performance of two water-based nanofluids in the thermal entrance region of a pipe. **Heat and Mass Transfer**, v. 59, n. 2, p. 329–345, 2023. Disponível em: <https://doi.org/10.1007/s00231-022-03265-4>

BRINKMAN, H. C. The Viscosity of Concentrated Suspensions and Solutions. **The Journal of Chemical Physics**, v. 20, n. 4, p. 571–571, 1952. Disponível em: <https://doi.org/10.1063/1.1700493>

BRUGGEMAN, D. A. G. Berechnung verschiedener physikalischer Konstanten von heterogenen Substanzen. I. Dielektrizitätskonstanten und Leitfähigkeiten der Mischkörper aus isotropen Substanzen. **Annalen der Physik**, v. 416, n. 7, p. 636–664, 1935. Disponível em: <https://doi.org/10.1002/andp.19354160705>

BULLEN, P. R.; CHEESEMAN, D. J.; HUSSAIN, L. A.; RUFFELLT, A. E. **The determination of pipe contraction pressure loss coefficients for incompressible turbulent flow.** [S. l.: s. n.].

BUONGIORNO, J. Convective Transport in Nanofluids. **Journal of Heat Transfer**, v. 128, n. 3, p. 240–250, 2006. Disponível em: <https://doi.org/10.1115/1.2150834>

BUSCHMANN, M. H.; AZIZIAN, R.; KEMPE, T.; JULIÁ, J. E.; MARTÍNEZ-CUENCA, R.; SUNDÉN, B.; WU, Z.; SEPPÄLÄ, A.; ALA-NISSILA, T. Correct interpretation of nanofluid convective heat transfer. **International Journal of Thermal Sciences**, v. 129, p. 504–531, 2018. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2017.11.003>

CACUA, K.; BUITRAGO-SIERRA, R.; PABÓN, E.; GALLEGU, A.; ZAPATA, C.; HERRERA, B. Nanofluids stability effect on a thermosyphon thermal performance. **International Journal of Thermal Sciences**, v. 153, p. 106347, 2020. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2020.106347>

CARDENAS CONTRERAS, E. M.; BANDARRA FILHO, E. P. Heat transfer performance of an automotive radiator with MWCNT nanofluid cooling in a high operating temperature range. **Applied Thermal Engineering**, v. 207, p. 118149, 2022. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2022.118149>

CÁRDENAS CONTRERAS, E. M.; OLIVEIRA, G. A.; BANDARRA FILHO, E. P. Experimental analysis of the thermohydraulic performance of graphene and silver nanofluids in automotive cooling systems. **International Journal of Heat and Mass Transfer**, v. 132, p. 375–387, 2019. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2018.12.014>

CÁRDENAS GÓMEZ, A. O.; PAZ ALEGRIAS, J. G.; BANDARRA FILHO, E. P. Experimental analysis of the thermal-hydraulic performance of water based silver and SWCNT nanofluids in single-phase flow. **Applied Thermal Engineering**, v. 124, p. 1176–1188, 2017. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2017.06.090>

CHAKRABORTY, S.; PANIGRAHI, P. K. Stability of nanofluid: A review. **Applied Thermal Engineering**, v. 174, p. 115259, 2020. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2020.115259>

CHALFI, T. Y.; GHIAASIAAN, S. M. Pressure drop caused by flow area changes in capillaries under low flow conditions. **International Journal of Multiphase Flow**, v. 34, n. 1, p. 2–12, 2008. Disponível em: <https://doi.org/10.1016/j.ijmultiphaseflow.2007.09.004>

CHAMSA-ARD, W.; BRUNDAVANAM, S.; FUNG, C. C.; FAWCETT, D.; POINERN, G. **Nanofluid types, their synthesis, properties and incorporation in direct solar thermal collectors: A review**. [S. l.: s. n.]. v. 7. Disponível em: <https://doi.org/10.3390/nano7060131>

CHEN, H.; REN, S.; ZHAO, Y.; WANG, H.; CUI, Y.; CHEN, Y.; WANG, Y.; YANG, H. Study on thermo-electrical performance of spray-cooled concentrating photovoltaic system using oleic acid modified nanofluid. **Solar Energy**, v. 269, p. 112358, 2024. Disponível em: <https://doi.org/10.1016/j.solener.2024.112358>

CHEN, M.; HE, Y.; HUANG, J.; ZHU, J. Investigation into Au nanofluids for solar photothermal conversion. **International Journal of Heat and Mass Transfer**, v. 108, p. 1894–1900, 2017. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2017.01.005>

CHILTON, T. H.; COLBURN, A. P. Mass Transfer (Absorption) Coefficients Prediction from Data on Heat Transfer and Fluid Friction. **Industrial & Engineering Chemistry**, v. 26, p. 1183–1187, 1934.

CHOWDHURY, S.; SHRIVASTAVA, S.; KAKATI, A.; SANGWAI, J. S. Comprehensive Review on the Role of Surfactants in the Chemical Enhanced Oil Recovery Process. **Industrial & Engineering Chemistry Research**, v. 61, n. 1, p. 21–64, 2022. Disponível em: <https://doi.org/10.1021/acs.iecr.1c03301>

CHRISTOPHER, D. S.; MADHUSUDHANA, G. R.; VENKUMAR, P.; KANNA, P. R.; MOHAMMED, H. A. Numerical investigation on laminar flow due to sudden expansion using nanofluids. **Journal of Computational and Theoretical Nanoscience**, v. 9, n. 12, p. 2217–2227, 2012. Disponível em: <https://doi.org/10.1166/jctn.2012.2642>

CHU, A.; LI, C.; ZHOU, Z.; LIU, B.; ZHANG, Y.; YANG, M.; GAO, T.; LIU, M.; ZHANG, N.; DAMBATTA, Y. S.; SHARMA, S. Nanofluids Minimal Quantity Lubrication Machining: From Mechanisms to Application. **Lubricants**, v. 11, n. 10, p. 422, 2023. Disponível em: <https://doi.org/10.3390/lubricants11100422>

COCCIA, G.; TOMASSETTI, S.; DI NICOLA, G. Thermal conductivity of nanofluids: A review of the existing correlations and a scaled semi-empirical equation. **Renewable and Sustainable Energy Reviews**, v. 151, p. 111573, 2021. Disponível em: <https://doi.org/10.1016/j.rser.2021.111573>

DAN, L.; ZHANG, K.; WANG, Q.; LIU, N. Surface modification boosts dispersion stability of nanoparticles in dielectric fluids. **Journal of Industrial and Engineering Chemistry**, v. 132, p. 518–528, 2024. Disponível em: <https://doi.org/10.1016/j.jiec.2023.11.046>

DAS, N. K.; MISHRA, D. K.; NAIK, P. K.; DEHURY, P.; BOSE, S.; BANERJEE, T. Dihydrolevoglycosenone as a novel bio-based nanofluid for thermal energy storage: Physiochemical and quantum chemical insights. **Journal of Energy Storage**, v. 59, p. 106365, 2023. Disponível em: <https://doi.org/10.1016/j.est.2022.106365>

DAS, P. K.; MALLIK, A. K.; MOLLA, A. H.; SANTRA, A. K.; GANGULY, R.; SAHA, A.; KUMAR, S.; ASWAL, V. K. Experimental investigation for stability and surface properties of

TiO₂ and Al₂O₃ water-based nanofluids. **Journal of Thermal Analysis and Calorimetry**, v. 147, n. 10, p. 5617–5635, 2022 a. Disponível em: <https://doi.org/10.1007/s10973-021-10894-0>

DAS, P. K.; MALLIK, A. K.; MOLLA, A. H.; SANTRA, A. K.; GANGULY, R.; SAHA, A.; KUMAR, S.; ASWAL, V. K. Experimental investigation for stability and surface properties of TiO₂ and Al₂O₃ water-based nanofluids. **Journal of Thermal Analysis and Calorimetry**, v. 147, n. 10, p. 5617–5635, 2022 b. Disponível em: <https://doi.org/10.1007/s10973-021-10894-0>

DAS, P. K.; SANTRA, A. K.; GANGULY, R.; DASH, S. K.; MUTHUSAMY, S.; SHA, M.; SADASIVUNI, K. K. An extensive review of preparation, stabilization, and application of single and hybrid nanofluids. **Journal of Thermal Analysis and Calorimetry**, 2024. Disponível em: <https://doi.org/10.1007/s10973-024-13449-1>

DEHGHAN, P.; KERAMAT, F.; MOFARAHI, M.; LEE, C.-H. Computational fluid dynamic analysis of graphene oxide/water nanofluid heat transfer over a double backward-facing microchannel. **Journal of the Taiwan Institute of Chemical Engineers**, v. 145, p. 104821, 2023. Disponível em: <https://doi.org/10.1016/j.jtice.2023.104821>

DEY, D.; SAHU, D. S. A review on the application of the nanofluids. **Heat Transfer**, v. 50, n. 2, p. 1113–1155, 2021. Disponível em: <https://doi.org/10.1002/htj.21920>

DEYMI, O.; HADAVIMOOGHADDAM, F.; ATASHROUZ, S.; NEDELJKOVIC, D.; ABUSWER, M. A.; HEMMATI-SARAPARDEH, A.; MOHADDESPOUR, A. Toward empirical correlations for estimating the specific heat capacity of nanofluids utilizing GRG, GP, GEP, and GMDH. **Scientific Reports**, v. 13, n. 1, p. 20763, 2023. Disponível em: <https://doi.org/10.1038/s41598-023-47327-x>

DITTUS, F. W.; BOELTER, L. M. K. Heat transfer in automobile radiators of the tubular type. **University of California Publications in Engineering**, v. 2, p. 443–461, 1930.

DONG, F.; WAN, J.; FENG, Y.; WANG, Z.; NI, J. Experimental Study on Thermophysical Properties of Propylene Glycol-Based Graphene Nanofluids. **International Journal of Thermophysics**, v. 42, n. 4, p. 46, 2021. Disponível em: <https://doi.org/10.1007/s10765-021-02798-w>

EANEST JEBASINGH, B.; VALAN ARASU, A. A comprehensive review on latent heat and thermal conductivity of nanoparticle dispersed phase change material for low-temperature applications. **Energy Storage Materials**, v. 24, p. 52–74, 2020 a. Disponível em: <https://doi.org/10.1016/j.ensm.2019.07.031>

EANEST JEBASINGH, B.; VALAN ARASU, A. A comprehensive review on latent heat and thermal conductivity of nanoparticle dispersed phase change material for low-temperature applications. **Energy Storage Materials**, v. 24, p. 52–74, 2020 b. Disponível em: <https://doi.org/10.1016/j.ensm.2019.07.031>

EASTMAN, J. A.; PHILLPOT, S. R.; CHOI, S. U. S.; KEBLINSKI, P. THERMAL TRANSPORT IN NANOFUIDS. **Annual Review of Materials Research**, v. 34, n. 1, p. 219–246, 2004. Disponível em: <https://doi.org/10.1146/annurev.matsci.34.052803.090621>

EINSTEIN, A. Eine neue Bestimmung der Moleküldimensionen. **Annalen der Physik**, v. 324, n. 2, p. 289–306, 1906. Disponível em: <https://doi.org/10.1002/andp.19063240204>

ELSAID, K.; ABDELKAREEM, M. A.; MAGHRABIE, H. M.; SAYED, E. T.; WILBERFORCE, T.; BAROUTAJI, A.; OLABI, A. G. Thermophysical properties of graphene-based nanofluids. **International Journal of Thermofluids**, v. 10, p. 100073, 2021. Disponível em: <https://doi.org/10.1016/j.ijft.2021.100073>

ERDEM, M.; VAROL, Y. Numerical investigation of heat transfer and flow characteristics of MHD nano-fluid forced convection in a pipe. **Journal of Thermal Analysis and Calorimetry**, v. 139, n. 6, p. 3897–3909, 2020. Disponível em: <https://doi.org/10.1007/s10973-020-09366-8>

EVERTS, M.; ROBBERTSE, P.; SPITHOLT, B. The effects of surface roughness on fully developed laminar and transitional flow friction factors and heat transfer coefficients in horizontal circular tubes. **International Journal of Heat and Mass Transfer**, v. 189, p. 122724, 2022. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2022.122724>

FADHL, B. M.; MAKHDOUM, B. M.; MA'ARIF, A.; SUWARNO, I.; HAMZAH, H.; SALEM, M. Dynamic viscosity modeling of nanofluids with MgO nanoparticles by utilizing intelligent methods. **Energy Reports**, v. 9, p. 5397–5403, 2023. Disponível em: <https://doi.org/10.1016/j.egyr.2023.04.369>

FARINHA, J. P. S. Bright and Stable Nanomaterials for Imaging and Sensing. **Polymers**, v. 15, n. 19, p. 3935, 2023. Disponível em: <https://doi.org/10.3390/polym15193935>

FLOREZ MORALES, D. A.; CÁRDENAS GOMEZ, A. O.; AMJAD, M.; DOS SANTOS, D. D.; BANDARRA FILHO, E. P. Experimental study on the heat transfer and pressure drop of oil-based nanofluids in laminar flow inside horizontal tubes. **Journal of the Brazilian Society of Mechanical Sciences and Engineering**, v. 45, n. 9, p. 467, 2023. Disponível em: <https://doi.org/10.1007/s40430-023-04412-6>

FRANKEL, N. A.; ACRIVOS, A. On the viscosity of a concentrated suspension of solid spheres. **Chemical Engineering Science**, v. 22, n. 6, p. 847–853, 1967. Disponível em: [https://doi.org/10.1016/0009-2509\(67\)80149-0](https://doi.org/10.1016/0009-2509(67)80149-0)

GANESH KUMAR, P.; SAKTHIVADIVEL, D.; MEIKANDAN, M.; VIGNESWARAN, V. S.; VELRAJ, R. Experimental study on thermal properties and electrical conductivity of stabilized H₂O-solar glycol mixture based multi-walled carbon nanotube nanofluids: developing a new correlation. **Heliyon**, v. 5, n. 8, p. e02385, 2019. Disponível em: <https://doi.org/10.1016/j.heliyon.2019.e02385>

GAO, Y.; HU, Q.; REN, Y.; WANG, X.; GUO, S.; HOU, Z.; GUO, P. Application of nanofluids in heat pipes. **Journal of Thermal Analysis and Calorimetry**, v. 148, n. 12, p. 5149–5177, 2023. Disponível em: <https://doi.org/10.1007/s10973-023-12115-2>

GAO, Y.; XI, Y.; ZHENZHONG, Y.; SASMITO, A.; MUJUMDAR, A.; WANG, L. Experimental investigation of specific heat of aqueous graphene oxide Al₂O₃ hybrid nanofluid. **Thermal Science**, v. 25, n. 1 Part B, p. 515–525, 2021. Disponível em: <https://doi.org/10.2298/TSCI190404381G>

GARCÍA-RINCÓN, M. A.; FLORES-PRIETO, J. J. Nanofluids stability in flat-plate solar collectors: A review. **Solar Energy Materials and Solar Cells**, v. 271, p. 112832, 2024. Disponível em: <https://doi.org/10.1016/j.solmat.2024.112832>

GARNETT, J. C. M. Coloured Metallic Films-Cause of Change on AnnealingNo.scent Crystals of Metal, Sphericnl Form. GARNBT'r, J. C. M. *Phil. Trans., A. [S. l.: s. n.]*. Disponível em: <https://royalsocietypublishing.org/>.

GEDİK, E.; TOPAL, M. A.; ERGÜN, A.; ACAR, B. Numerical investigation of Al₂O₃- water nanofluid flow and heat transfer in sudden expansion channels. *In*: 2015, **Anais [...]**. [S. l.: s. n.]

GNIELINSKI, V. Neue Gleichungen für den Wärme- und den Stoffübergang in turbulent durchströmten Rohren und Kanälen. **Forschung im Ingenieurwesen**, v. 41, n. 1, p. 8–16, 1975. Disponível em: <https://doi.org/10.1007/BF02559682>

GONÇALVES, I.; SOUZA, R.; COUTINHO, G.; MIRANDA, J.; MOITA, A.; PEREIRA, J. E.; MOREIRA, A.; LIMA, R. Thermal Conductivity of Nanofluids: A Review on Prediction Models, Controversies and Challenges. **Applied Sciences**, v. 11, n. 6, p. 2525, 2021. Disponível em: <https://doi.org/10.3390/app11062525>

GRAHAM, A. L. On the viscosity of suspensions of solid spheres. **Applied Scientific Research**, v. 37, n. 3–4, p. 275–286, 1981. Disponível em: <https://doi.org/10.1007/BF00951252>

GÜCÜYEN, E.; TUĞRUL ERDEM, R.; GÖKKUŞ, Ü. NUMERICAL MODELLING OF SUDDEN CONTRACTION IN PIPE FLOWS **Sigma J Eng & Nat Sci**. [S. l.: s. n.].

GUO, H.; WANG, L.; YU, J.; YE, F.; MA, C.; LI, Z. Local resistance of fluid flow across sudden contraction in small channels. **Frontiers of Energy and Power Engineering in China**, v. 4, n. 2, p. 149–154, 2010. Disponível em: <https://doi.org/10.1007/s11708-009-0060-7>

GUPTA, M.; SINGH, V.; KUMAR, R.; SAID, Z. A review on thermophysical properties of nanofluids and heat transfer applications. **Renewable and Sustainable Energy Reviews**, v. 74, p. 638–670, 2017. Disponível em: <https://doi.org/10.1016/j.rser.2017.02.073>

GÜRSOY, E.; KADIR PAZARLIOĞLU, H.; DAĞDEVİREN, A.; GÜRDAL, M.; GEDİK, E.; ARSLAN, K.; KURT, H. Energy analysis of magnetite nanofluid flowing in newly designed sudden expansion tube retrofitted with dimpled fin. **International Journal of Heat and Mass Transfer**, v. 199, p. 123446, 2022. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123446>

GÜRSOY, E.; PAZARLIOĞLU, H. K.; GÜRDAL, M.; GEDİK, E.; ARSLAN, K. Parametric analysis of different Al₂O₃ nanoparticle shapes and expansion angles for sudden expanded tube

regarding the first law of thermodynamics. **International Journal of Thermal Sciences**, v. 197, p. 108759, 2024. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2023.108759>

HAMILTON, R. L.; CROSSER, O. K. Thermal Conductivity of Heterogeneous Two-Component Systems. **Industrial & Engineering Chemistry Fundamentals**, v. 1, n. 3, p. 187–191, 1962. Disponível em: <https://doi.org/10.1021/i160003a005>

HAMZE, S.; BERRADA, N.; DESFORGES, A.; VIGOLO, B.; GLEIZE, J.; GHANBAJA, J.; MARÉ, T.; CABALEIRO, D.; ESTELLÉ, P. Dynamic Viscosity of Purified Multi-Walled Carbon Nanotubes Water and Water-Propylene Glycol-Based Nanofluids. **Heat Transfer Engineering**, v. 42, n. 19–20, p. 1663–1674, 2021. Disponível em: <https://doi.org/10.1080/01457632.2020.1818382>

HAMZE, S.; CABALEIRO, D.; ESTELLÉ, P. Graphene-based nanofluids: A comprehensive review about rheological behavior and dynamic viscosity. **Journal of Molecular Liquids**, v. 325, p. 115207, 2021. Disponível em: <https://doi.org/10.1016/j.molliq.2020.115207>

HAQUE, M. E.; HOSSAIN, M. S.; ALI, H. M. Laminar forced convection heat transfer of nanofluids inside non-circular ducts: A review. **Powder Technology**, v. 378, p. 808–830, 2021. Disponível em: <https://doi.org/10.1016/j.powtec.2020.10.042>

HASHIM, N. M. R.; YUSOFF, Mohd. Z.; MOHAMMED, H. A. Turbulent forced convection flow of nanofluids over triple forward facing step. **World Journal of Engineering**, v. 14, n. 4, p. 263–278, 2017. Disponível em: <https://doi.org/10.1108/WJE-07-2016-0024>

HATAMI, M.; JING, D. Introduction to nanofluids. In: **Nanofluids**. [S. l.]: Elsevier, 2020. p. 1–50. Disponível em: <https://doi.org/10.1016/B978-0-08-102933-6.00001-9>

HAUSER, E. A. The history of colloid science: In memory of Wolfgang Ostwald. **Journal of Chemical Education**, v. 32, n. 1, p. 2, 1955. Disponível em: <https://doi.org/10.1021/ed032p2>

HENTSCHKE, R. On the specific heat capacity enhancement in nanofluids. **Nanoscale Research Letters**, v. 11, n. 1, p. 88, 2016. Disponível em: <https://doi.org/10.1186/s11671-015-1188-5>

HESHMATI, A.; MOHAMMED, H. A.; DARUS, A. N. Mixed convection heat transfer of nanofluids over backward facing step having a slotted baffle. **Applied Mathematics and**

Computation, v. 240, p. 368–386, 2014. Disponível em: <https://doi.org/10.1016/j.amc.2014.04.058>

HILO, A. K.; TALIB, A. R. A.; IBORRA, A. A.; SULTAN, M. T. H.; HAMID, M. F. A. Experimental study of nanofluids flow and heat transfer over a backward-facing step channel. **Powder Technology**, v. 372, p. 497–505, 2020. Disponível em: <https://doi.org/10.1016/j.powtec.2020.06.013>

HO, C. J.; LIU, Y.-C.; YANG, T.-F.; GHALAMBAZ, M.; YAN, W.-M. Convective heat transfer of nano-encapsulated phase change material suspension in a divergent minichannel heatsink. **International Journal of Heat and Mass Transfer**, v. 165, p. 120717, 2021. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2020.120717>

HOLMAN, J. P. **Heat transfer**. 10th. ed. New York: McGraw - Hill Professional, 2009.

HOLMAN, J. P. **EXPERIMENTAL METHODS FOR ENGINEERS**. Eighth Edi ed. New York: McGraw-Hill, 2011.

HOSSEINI, M.; ABDELRAZEK, A. H.; SADRI, R.; MALLAH, A. R.; KAZI, S. N.; CHEW, B. T.; ROZALI, S.; YUSOFF, N. Numerical study of turbulent heat transfer of nanofluids containing eco-friendly treated carbon nanotubes through a concentric annular heat exchanger. **International Journal of Heat and Mass Transfer**, v. 127, p. 403–412, 2018. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.040>

HOSSEINI, S. M.; SAFAEI, M. R.; GOODARZI, M.; ALRASHED, A. A. A. A.; NGUYEN, T. K. New temperature, interfacial shell dependent dimensionless model for thermal conductivity of nanofluids. **International Journal of Heat and Mass Transfer**, v. 114, p. 207–210, 2017. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2017.06.061>

ILYAS, S. U.; PENDYALA, R.; MARNENI, N. Stability of Nanofluids. In: [S. l.: s. n.]. p. 1–31. Disponível em: https://doi.org/10.1007/978-3-319-29761-3_1

ISA, R. M.; SATIA, M. S. D.; MAMAT, H.; ABDULLAH, M. Z. Performance of Functionalized MWCNT–Water Nanofluids for Heat Transfer Applications. **Arabian Journal for Science and Engineering**, v. 45, n. 7, p. 5603–5614, 2020. Disponível em: <https://doi.org/10.1007/s13369-020-04515-5>

JALILI, B.; EMAD, M.; JALILI, P.; DOMIRI GANJI, D.; SALEEM, S.; TAG-ELDIN, E. M. Thermal analysis of boundary layer nanofluid flow over the movable plate with internal heat generation, radiation, and viscous dissipation. **Case Studies in Thermal Engineering**, v. 49, p. 103203, 2023. Disponível em: <https://doi.org/10.1016/j.csite.2023.103203>

JAMEI, M.; AHMADIANFAR, I.; OLUMEGBON, I. A.; ASADI, A.; KARBASI, M.; SAID, Z.; SHARIFPUR, M.; MEYER, J. P. On the specific heat capacity estimation of metal oxide-based nanofluid for energy perspective – A comprehensive assessment of data analysis techniques. **International Communications in Heat and Mass Transfer**, v. 123, p. 105217, 2021. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2021.105217>

JEFFREY, D. J. **Conduction Through a Random Suspension of Spheres**Source: **Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences**. [S. l.: s. n.]. Disponível em: <https://www.jstor.org/stable/78573>.

JIANG, L.; GAO, L.; SUN, J. Production of aqueous colloidal dispersions of carbon nanotubes. **Journal of Colloid and Interface Science**, v. 260, n. 1, p. 89–94, 2003. Disponível em: [https://doi.org/10.1016/S0021-9797\(02\)00176-5](https://doi.org/10.1016/S0021-9797(02)00176-5)

JIN, W.; JIANG, L.; HAN, L.; HUANG, H.; ZHANG, J.; GUO, M.; GU, Y.; ZHI, F.; CHEN, Z.; YANG, G. Investigation of thermal conductivity enhancement of water-based graphene and graphene/MXene nanofluids. **Journal of Molecular Liquids**, v. 367, p. 120455, 2022. Disponível em: <https://doi.org/10.1016/j.molliq.2022.120455>

KALSI, S.; KUMAR, S.; KUMAR, A.; ALAM, T.; DOBROTĂ, D. Thermophysical properties of nanofluids and their potential applications in heat transfer enhancement: A review. **Arabian Journal of Chemistry**, v. 16, n. 11, p. 105272, 2023. Disponível em: <https://doi.org/10.1016/j.arabjc.2023.105272>

KANNA, P. R.; TALER, J.; ANBUMALAR, V.; SANTHOSH KUMAR, A. V.; PUSHPARAJ, A.; CHRISTOPHER, D. S. Conjugate heat transfer from sudden expansion using nanofluid. **Numerical Heat Transfer; Part A: Applications**, v. 67, n. 1, p. 75–99, 2015. Disponível em: <https://doi.org/10.1080/10407782.2014.915685>

KANTI, P.; SHARMA, K. V.; KHEDKAR, R. S.; REHMAN, T. Synthesis, characterization, stability, and thermal properties of graphene oxide based hybrid nanofluids for thermal

applications: Experimental approach. **Diamond and Related Materials**, v. 128, p. 109265, 2022. Disponível em: <https://doi.org/10.1016/j.diamond.2022.109265>

KAOOD, A.; HASSAN, M. A. Thermo-hydraulic performance of nanofluids flow in various internally corrugated tubes. **Chemical Engineering and Processing - Process Intensification**, v. 154, p. 108043, 2020. Disponível em: <https://doi.org/10.1016/j.cep.2020.108043>

KARAMI, F.; ABBASIAN ARANI, A. A.; AKBARI, O. A.; POURFATTAH, F.; TOGHRAIE, D. Numerical study of location and depth of rectangular grooves on the turbulent heat transfer performance and characteristics of CuO-water nanofluid flow. **Heliyon**, v. 9, n. 3, p. e14239, 2023. Disponível em: <https://doi.org/10.1016/j.heliyon.2023.e14239>

KARIMI BAKHTIYAR, N.; JAVADPOUR, R.; ZEINALI HERIS, S.; MOHAMMADPOURFARD, M. Improving the thermal characteristics of a cooling tower by replacing the operating fluid with functionalized and non-functionalized aqueous MWCNT nanofluids. **Case Studies in Thermal Engineering**, v. 39, p. 102422, 2022. Disponível em: <https://doi.org/10.1016/j.csite.2022.102422>

KAYS, W. M. **LOSS COEFFICIENTS FOR ABRUPT CHANGES IN FLOW CROSS SECTION WITH LOW REYNOLDS NUMBER FLOW IN SINGLE AND MULTIPLE TUBE SYSTEMS. Technical Report No. 9.** [S. l.: s. n.].

KAZI, S. N.; TOGUN, H. Heat Transfer and Nanofluid Flow Through Different Geometries. **Heat Transfer Studies and Applications**, 2015. Disponível em: <https://doi.org/10.5772/61075>

KEKLIKCIOGLU, O.; DAGDEVIR, T.; OZCEYHAN, V. Heat transfer and pressure drop investigation of graphene nanoplatelet-water and titanium dioxide-water nanofluids in a horizontal tube. **Applied Thermal Engineering**, v. 162, p. 114256, 2019. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2019.114256>

KHAJEH ARZANI, H.; AMIRI, A.; ARZANI, H. K.; ROZALI, S. Bin; KAZI, S. N.; BADARUDIN, A. Toward improved heat transfer performance of annular heat exchangers with water/ethylene glycol-based nanofluids containing graphene nanoplatelets. **Journal of Thermal Analysis and Calorimetry**, v. 126, n. 3, p. 1427–1436, 2016. Disponível em: <https://doi.org/10.1007/s10973-016-5663-8>

KHERBEET, A. S.; MOHAMMED, H. A.; MUNISAMY, K. M.; SAIDUR, R.; SALMAN, B. H.; MAHBUBUL, I. M. Experimental and numerical study of nanofluid flow and heat transfer over microscale forward-facing step. **International Communications in Heat and Mass Transfer**, v. 57, p. 319–329, 2014. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2014.07.028>

KHERBEET, A. S.; MOHAMMED, H. A.; SALMAN, B. H. The effect of nanofluids flow on mixed convection heat transfer over microscale backward-facing step. **International Journal of Heat and Mass Transfer**, v. 55, n. 21–22, p. 5870–5881, 2012. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2012.05.084>

KHERBEET, A. S.; MOHAMMED, H. A.; SALMAN, B. H.; AHMED, H. E.; ALAWI, O. A.; RASHIDI, M. M. Experimental study of nanofluid flow and heat transfer over microscale backward- and forward-facing steps. **Experimental Thermal and Fluid Science**, v. 65, p. 13–21, 2015. Disponível em: <https://doi.org/10.1016/j.expthermflusci.2015.02.023>

KIA, S.; KHANMOHAMMADI, S.; JAHANGIRI, A. Experimental and numerical investigation on heat transfer and pressure drop of SiO₂ and Al₂O₃ oil-based nanofluid characteristics through the different helical tubes under constant heat fluxes. **International Journal of Thermal Sciences**, v. 185, p. 108082, 2023. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2022.108082>

KIMOUCHE, A.; MATAOUI, A.; OZTOP, H. F.; ABU-HAMDEH, N. Analysis of heat transfer of different nanofluids flow through an abrupt expansion pipe. **Applied Thermal Engineering**, v. 112, p. 965–974, 2017. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2016.10.140>

KLAZLY, M.; BOGNAR, G. Heat transfer enhancement for nanofluid flows over a microscale backward-facing step. **Alexandria Engineering Journal**, v. 61, n. 10, p. 8161–8176, 2022. Disponível em: <https://doi.org/10.1016/j.aej.2022.01.008>

KLINE, S.; MCCLINTOCK, F. Describing Uncertainties in Single-Sample Experiments. **Mechanical Engineering**, v. 75, p. 3–8, 1953.

KULKARNI, D. P.; DAS, D. K.; CHUKWU, G. A. Temperature Dependent Rheological Property of Copper Oxide Nanoparticles Suspension (Nanofluid). **Journal of Nanoscience and**

Nanotechnology, v. 6, n. 4, p. 1150–1154, 2006. Disponível em: <https://doi.org/10.1166/jnn.2006.187>

KUMAR, S. P.; SHENOY, U. S.; BHAT, D. K. A direct approach towards synthesis of copper nanofluid by one step solution phase method. **Journal of Crystal Growth**, v. 630, p. 127591, 2024. Disponível em: <https://doi.org/10.1016/j.jcrysgro.2024.127591>

LE BA, T.; MAHIAN, O.; WONGWISES, S.; SZILÁGYI, I. M. Review on the recent progress in the preparation and stability of graphene-based nanofluids. **Journal of Thermal Analysis and Calorimetry**, v. 142, n. 3, p. 1145–1172, 2020. Disponível em: <https://doi.org/10.1007/s10973-020-09365-9>

LENIN, R.; JOY, P. A.; BERA, C. A review of the recent progress on thermal conductivity of nanofluid. **Journal of Molecular Liquids**, v. 338, p. 116929, 2021. Disponível em: <https://doi.org/10.1016/j.molliq.2021.116929>

LI, X.; CHEN, W.; ZOU, C. The stability, viscosity and thermal conductivity of carbon nanotubes nanofluids with high particle concentration: A surface modification approach. **Powder Technology**, v. 361, p. 957–967, 2020. Disponível em: <https://doi.org/10.1016/j.powtec.2019.10.106>

LI, Y.; ZHOU, J.; TUNG, S.; SCHNEIDER, E.; XI, S. A review on development of nanofluid preparation and characterization. **Powder Technology**, v. 196, n. 2, p. 89–101, 2009 a. Disponível em: <https://doi.org/10.1016/j.powtec.2009.07.025>

LI, Y.; ZHOU, J.; TUNG, S.; SCHNEIDER, E.; XI, S. A review on development of nanofluid preparation and characterization. **Powder Technology**, v. 196, n. 2, p. 89–101, 2009 b. Disponível em: <https://doi.org/10.1016/j.powtec.2009.07.025>

LI, Z.; SHAFEE, A.; TLILI, I.; JAFARYAR, M. Chapter 2 - Nanofluid for heat exchangers. In: LI, Z.; SHAFEE, A.; TLILI, I.; JAFARYAR, M. (org.). **Nanofluid in Heat Exchangers for Mechanical Systems**. [S. l.]: Elsevier, 2020. p. 59–73. *E-book*. Disponível em: <https://doi.org/https://doi.org/10.1016/B978-0-12-821923-2.00002-6>

LIN, H.; JIAN, Q.; BAI, X.; LI, D.; HUANG, Z.; HUANG, W.; FENG, S.; CHENG, Z. Recent advances in thermal conductivity and thermal applications of graphene and its derivatives

nanofluids. **Applied Thermal Engineering**, v. 218, p. 119176, 2023. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2022.119176>

LIU, Y.; GE, X.; LI, J. Graphene lubrication. **Applied Materials Today**, v. 20, p. 100662, 2020. Disponível em: <https://doi.org/10.1016/j.apmt.2020.100662>

LUNDGREN, T. S. Slow flow through stationary random beds and suspensions of spheres. **Journal of Fluid Mechanics**, v. 51, n. 2, p. 273–299, 1972. Disponível em: <https://doi.org/10.1017/S002211207200120X>

MA, Y.; MOHEBBI, R.; RASHIDI, M. M.; YANG, Z.; FANG, Y. Baffle and geometry effects on nanofluid forced convection over forward- and backward-facing steps channel by means of lattice Boltzmann method. **Physica A: Statistical Mechanics and its Applications**, v. 554, n. 4800, 2020. Disponível em: <https://doi.org/10.1016/j.physa.2020.124696>

MACHUNO, L. G. B.; OLIVEIRA, A. R.; FURLAN, R. H.; LIMA, A. B.; MORAIS, L. C.; GELAMO, R. V. Multilayer Graphene Films Obtained by Dip Coating Technique. **Materials Research**, v. 18, n. 4, p. 775–780, 2015. Disponível em: <https://doi.org/10.1590/1516-1439.005415>

MAHMOOD, D. T.; HILAL, K. H.; AUN, S. H. A. Numerical investigation of heat transfer characteristics and flow structure inside sudden expansion channel. *In: 2024, Anais [...]. [S. l.: s. n.] p. 080006.* Disponível em: <https://doi.org/10.1063/5.0206525>

MAHMOUDI, A. H.; POP, I.; SHAHI, M. Effect of magnetic field on natural convection in a triangular enclosure filled with nanofluid. **International Journal of Thermal Sciences**, v. 59, p. 126–140, 2012. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2012.04.006>

MARQUARDT, D. W. An Algorithm for Least-Squares Estimation of Nonlinear Parameters. **Journal of the Society for Industrial and Applied Mathematics**, v. 11, n. 2, p. 431–441, 1963. Disponível em: <https://doi.org/10.1137/0111030>

MASOUD HOSSEINI, S.; MOGHADASSI, A. R.; HENNEKE, D. E. A new dimensionless group model for determining the viscosity of nanofluids. **J. Therm. Anal. Calorim.**, v. 100, n. 3, p. 873–877, 2010.

MASOUMI, N.; SOHRABI, N.; BEHZADMEHR, A. A new model for calculating the effective viscosity of nanofluids. **Journal of Physics D: Applied Physics**, v. 42, n. 5, p. 055501, 2009. Disponível em: <https://doi.org/10.1088/0022-3727/42/5/055501>

MAXWELL, J. C. **A treatise on electricity and magnetism**. [S. l.]: Clarendon press, 1873. v. 1.

MENG, G.; CHEN, G.; TAN, Z.; WANG, Z. Fluid flow and heat transfer of carbon nanotubes- or graphene nano platelets-based nanofluids in a channel with micro-cylinders: an experimental study. **Heat and Mass Transfer**, v. 58, n. 12, p. 2221–2234, 2022. Disponível em: <https://doi.org/10.1007/s00231-022-03236-9>

MERCAN, H. Introduction to nanofluids, challenges, and opportunities. In: **Nanofluids and Mass Transfer**. [S. l.]: Elsevier, 2022. p. 3–20. Disponível em: <https://doi.org/10.1016/B978-0-12-823996-4.00001-X>

MINAKOV, A. V.; GUZEL, D. V.; PRYAZHNIKOV, M. I.; ZHIGAREV, V. A.; RUDYAK, V. Ya. Study of turbulent heat transfer of the nanofluids in a cylindrical channel. **International Journal of Heat and Mass Transfer**, v. 102, p. 745–755, 2016. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2016.06.071>

MISHRA, P. C.; MUKHERJEE, S.; NAYAK, S. K.; PANDA, A. A brief review on viscosity of nanofluids. **International Nano Letters**, v. 4, n. 4, p. 109–120, 2014. Disponível em: <https://doi.org/10.1007/s40089-014-0126-3>

MOHAMMAD, R. S.; ALDLEMY, M. S.; AHMED, A. M.; FALAH, M. W.; AHAMMED, S. J.; YASEEN, Z. M. Thermal Analysis of Graphene-Based Nanofluids for Energy System and Economic Feasibility. **Journal of Nanomaterials**, v. 2022, n. 1, 2022. Disponível em: <https://doi.org/10.1155/2022/3530419>

MOHAMMAD, R. S.; ALDLEMY, M. S.; HASSAN, M. S. Al; ABDULLA, A. I.; SCHOLZ, M.; YASEEN, Z. M. Frictional Pressure Drop and Cost Savings for Graphene Nanoplatelets Nanofluids in Turbulent Flow Environments. **Nanomaterials**, v. 11, n. 11, p. 3094, 2021. Disponível em: <https://doi.org/10.3390/nano11113094>

MONTAZER, E.; SALAMI, E.; YARMAND, H.; CHOWDHURY, Z. Z.; DAHARI, M.; KAZI, S. N.; BADARUDIN, A. Development of a new density correlation for carbon-based nanofluids using response surface methodology. **Journal of Thermal Analysis and Calorimetry**, v. 132, n. 2, p. 1399–1407, 2018. Disponível em: <https://doi.org/10.1007/s10973-018-6978-4>

MONTAZER, E.; SHAFIL, M. B.; SALAMI, E.; MUHAMAD, M. R.; YARMAND, H.; GHAREHKHANI, S.; CHOWDHURY, Z. Z.; KAZI, S. N.; BADARUDIN, A. Heat transfer in turbulent nanofluids: Separation flow studies and development of novel correlations. **Advanced Powder Technology**, v. 31, n. 8, p. 3120–3133, 2020 a. Disponível em: <https://doi.org/10.1016/j.appt.2020.06.001>

MONTAZER, E.; SHAFIL, M. B.; SALAMI, E.; MUHAMAD, M. R.; YARMAND, H.; GHAREHKHANI, S.; CHOWDHURY, Z. Z.; KAZI, S. N.; BADARUDIN, A. Heat transfer in turbulent nanofluids: Separation flow studies and development of novel correlations. **Advanced Powder Technology**, v. 31, n. 8, p. 3120–3133, 2020 b. Disponível em: <https://doi.org/10.1016/j.appt.2020.06.001>

MOOSAVI, R.; JALIL, E.; LIN, C. X. Turbulent forced convection nanofluid flow over an inclined forward-facing step. **Heat Transfer Research**, v. 51, n. 13, p. 1221–1240, 2021. Disponível em: <https://doi.org/10.1615/heattransres.2020034082>

MORADI, A.; TOGHRAIE, D.; ISFAHANI, A. H. M.; HOSSEINIAN, A. An experimental study on MWCNT–water nanofluids flow and heat transfer in double-pipe heat exchanger using porous media. **Journal of Thermal Analysis and Calorimetry**, v. 137, n. 5, p. 1797–1807, 2019. Disponível em: <https://doi.org/10.1007/s10973-019-08076-0>

MOUSAVI, H.; GHOMSHE, S. M. T.; RASHIDI, A.; MIRZAEI, M. Hybrids carbon quantum dots as new nanofluids for heat transfer enhancement in wet cooling towers. **Heat and Mass Transfer**, v. 58, n. 2, p. 309–320, 2022. Disponível em: <https://doi.org/10.1007/s00231-021-03077-y>

MOZAFARY, B.; AKBAR, A.; ARANI, A.; SHEIKHZADEH NOOSHABADI, G. A.; SALIMI, M. Brownian motion models effect on the nanofluid fluid flow and heat transfer in

the natural, mixed, and forced convection. **Journal of Thermal Engineering**, v. 10, n. 1, p. 88–100, 2024. Disponível em: <https://doi.org/10.18186/thermal.1429382>

MU'AZ MUHAMMAD, N.; AZWADI, N.; SIDIK, C.; SAAT, A.; ABDULLAHI, B. CFD Letters Effect of Nanofluids on Heat Transfer and Pressure Drop Characteristics of Diverging-Converging Minichannel heat sink. **CFD Letters**, v. 11, p. 105–120, 2019.

MUKESH KUMAR, P. C.; CHANDRASEKAR, M. Heat transfer and friction factor analysis of MWCNT nanofluids in double helically coiled tube heat exchanger. **Journal of Thermal Analysis and Calorimetry**, v. 144, n. 1, p. 219–231, 2021. Disponível em: <https://doi.org/10.1007/s10973-020-09444-x>

MUKHERJEE, S.; CHAKRABARTY, S.; MISHRA, P. C.; CHAUDHURI, P. Stability and sedimentation characteristics of water based Al_2O_3 and TiO_2 nanofluids. **Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanomaterials, Nanoengineering and Nanosystems**, v. 238, n. 1–2, p. 17–30, 2024. Disponível em: <https://doi.org/10.1177/23977914221127735>

MURSHED, S. M. S.; LEONG, K. C.; YANG, C. Enhanced thermal conductivity of TiO_2 —water based nanofluids. **International Journal of Thermal Sciences**, v. 44, n. 4, p. 367–373, 2005. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2004.12.005>

MURSHED, S. M. S.; LEONG, K. C.; YANG, C. A combined model for the effective thermal conductivity of nanofluids. **Applied Thermal Engineering**, v. 29, n. 11–12, p. 2477–2483, 2009. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2008.12.018>

MURTHY H M, S.; HEGDE, R. N.; RAI, N. Conjoint effect of turbulator and Al_2O_3 nanofluids on DPHEs thermal performance: Experimental study. **Heat and Mass Transfer**, v. 60, n. 6, p. 933–953, 2024. Disponível em: <https://doi.org/10.1007/s00231-024-03460-5>

NABATI SHOGLI, S.; JAMALI, J.; KESHAVARZ MORAVEJI, M. Electrical conductivity, viscosity, and density of different nanofluids: An experimental study. **Experimental Thermal and Fluid Science**, v. 74, p. 339–346, 2016. Disponível em: <https://doi.org/10.1016/j.expthermflusci.2016.01.004>

NAGARAJAN, P.; SOMA SUNDARAM, S. The effect of appendages at step on heat transfer in a backward-facing step. **International Communications in Heat and Mass Transfer**, v. 155, p. 107589, 2024. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2024.107589>

NATESAN, K.; KARINKA, S. A comprehensive review of heat transfer enhancement of heat exchanger, heat pipe and electronic components using graphene. **Case Studies in Thermal Engineering**, v. 45, p. 102874, 2023. Disponível em: <https://doi.org/10.1016/j.csite.2023.102874>

NATH, R.; KRISHNAN, M. Numerical study of double diffusive mixed convection in a backward facing step channel filled with Cu-water nanofluid. **International Journal of Mechanical Sciences**, v. 153–154, n. January, p. 48–63, 2019 a. Disponível em: <https://doi.org/10.1016/j.ijmecsci.2019.01.035>

NATH, R.; KRISHNAN, M. Numerical study of double diffusive mixed convection in a backward facing step channel filled with Cu-water nanofluid. **International Journal of Mechanical Sciences**, v. 153–154, n. January, p. 48–63, 2019 b. Disponível em: <https://doi.org/10.1016/j.ijmecsci.2019.01.035>

NATH, R.; KRISHNAN, M. Numerical study of double diffusive mixed convection in a backward facing step channel filled with Cu-water nanofluid. **International Journal of Mechanical Sciences**, v. 153–154, p. 48–63, 2019 c. Disponível em: <https://doi.org/10.1016/j.ijmecsci.2019.01.035>

NOORZADEH, S.; SADEGH MOGHANLOU, F.; VAJDI, M.; ATAELI, M. Thermal conductivity, viscosity and heat transfer process in nanofluids: A critical review. **Journal of Composites and Compounds**, v. 2, n. 5, p. 175–192, 2020. Disponível em: <https://doi.org/10.29252/jcc.2.4.3>

NOURI, D.; PASANDIDEH-FARD, M.; JAVAD OBOODI, M.; MAHIAN, O.; SAHIN, A. Z. Entropy generation analysis of nanofluid flow over a spherical heat source inside a channel with sudden expansion and contraction. **International Journal of Heat and Mass Transfer**, v. 116, p. 1036–1043, 2018. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.097>

OHMAE, N. **Editors : M J Neale , M Priest and G Stachowiak.** [S. l.: s. n.].

OLIVEIRA, A. M.; MESQUITA, A. Z.; MARQUES, J. G. de O.; FILHO, E. P. B.; PALMA, D. A. P. Experimental Evaluation of Thermal Conductivity and Other Thermophysical Properties of Nanofluids Based on Functionalized (-OH) Mwcnt Nanoparticles Dispersed in Distilled Water. **Advances in Nanoparticles**, v. 12, n. 01, p. 32–52, 2023. Disponível em: <https://doi.org/10.4236/anp.2023.121004>

OLIVEIRA, G. A.; CARDENAS CONTRERAS, E. M.; BANDARRA FILHO, E. P. Experimental study of thermophysical properties of MWCNT and graphene coolant nanofluids for automotive application. **Journal of the Brazilian Society of Mechanical Sciences and Engineering**, v. 43, n. 3, p. 140, 2021. Disponível em: <https://doi.org/10.1007/s40430-021-02870-4>

ONYIRIUKA, E. Modelling the thermal conductivity of nanofluids using a novel model of models approach. **Journal of Thermal Analysis and Calorimetry**, v. 148, n. 23, p. 13569–13585, 2023. Disponível em: <https://doi.org/10.1007/s10973-023-12642-y>

OON, C. S.; TOGUN, H.; KAZI, S. N.; BADARUDIN, A.; ZUBIR, M. N. M.; SADEGHINEZHAD, E. Numerical simulation of heat transfer to separation air flow in an annular pipe. **International Communications in Heat and Mass Transfer**, v. 39, n. 8, p. 1176–1180, 2012. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2012.06.019>

OZTOP, H. F.; DAGTEKIN, I. Enhancement of heat transfer in a pipe with inner contraction-expansion-contraction pipe insertion. **International Communications in Heat and Mass Transfer**, v. 30, n. 08, p. 1157–1168, 2003. Disponível em: [https://doi.org/http://dx.doi.org/10.1016/S0735-1933\(03\)00181-7](https://doi.org/http://dx.doi.org/10.1016/S0735-1933(03)00181-7)

PAK, B. C.; CHO, Y. I. HYDRODYNAMIC AND HEAT TRANSFER STUDY OF DISPERSED FLUIDS WITH SUBMICRON METALLIC OXIDE PARTICLES. **Experimental Heat Transfer**, v. 11, n. 2, p. 151–170, 1998. Disponível em: <https://doi.org/10.1080/08916159808946559>

PAVITHRA, K. S.; GURUMURTHY, S. C.; YASHODA, M. P.; MATETI, T.; RAMAM, K.; NAYAK, R.; MURARI, M. S. Polymer-dispersant-stabilized Ag nanofluids for heat transfer applications. **Journal of Thermal Analysis and Calorimetry**, v. 146, n. 2, p. 601–610, 2021. Disponível em: <https://doi.org/10.1007/s10973-020-10064-8>

PAWAR, J. B.; JAWALE, A. M.; TUNGKAR, V. B. Al₂O₃/distilled water-based nanofluid process parameter optimization for thermal conductivity. *In: 2024, Anais [...]. [S. l.: s. n.] p. 040001.* Disponível em: <https://doi.org/10.1063/5.0214092>

PAZARLIOĞLU, H. K.; GÜRSOY, E.; GÜRDAL, M.; SAID, Z.; ARSLAN, K.; GEDIK, E. Numerical simulation of sudden expansion tubes with Ag-MgO nanofluid and innovative fin structure: A thermo-fluidic analysis. **International Journal of Heat and Fluid Flow**, v. 108, p. 109448, 2024. Disponível em: <https://doi.org/10.1016/j.ijheatfluidflow.2024.109448>

POUR, M. S.; NASSAB, S. A. G. Numerical Investigation of Forced Laminar Convection Flow of Nanofluids Over a Backward Facing Step Under Bleeding Condition. **Journal of Mechanics**, v. 28, n. 2, p. N7–N12, 2012. Disponível em: <https://doi.org/10.1017/jmech.2012.45>

POZZI, M.; JONAK DUTTA, S.; KUNTZE, M.; BADING, J.; RÜSSBÜLT, J. S.; FABIG, C.; LANGFELDT, M.; SCHULZ, F.; HORCAJADA, P.; PARAK, W. J. Visualization of the High Surface-to-Volume Ratio of Nanomaterials and Its Consequences. **Journal of Chemical Education**, v. 101, n. 8, p. 3146–3155, 2024. Disponível em: <https://doi.org/10.1021/acs.jchemed.4c00089>

PRASAD, A. R.; SINGH, S.; NAGAR, H. A Review on Nanofluids: Properties and Applications. **International Journal Of Advance Research And Innovative Ideas In Education**, v. 3, p. 3185–3209, 2017.

QI, C.; DING, Z.; TU, J.; WANG, Y.; WANG, Y. Study on backward-facing step flow and heat transfer characteristics of hybrid nanofluids. **Journal of Thermal Analysis and Calorimetry**, v. 144, p. 2269–2284, 2020.

QI, C.; DING, Z.; TU, J.; WANG, Y.; WANG, Y. Study on backward-facing step flow and heat transfer characteristics of hybrid nanofluids. **Journal of Thermal Analysis and Calorimetry**, v. 144, n. 6, p. 2269–2284, 2021. Disponível em: <https://doi.org/10.1007/s10973-020-10379-6>

RAISI, A.; AMINOSSADATI, S. M.; GHASEMI, B. An innovative nanofluid-based cooling using separated natural and forced convection in low Reynolds flows. **Journal of the Taiwan Institute of Chemical Engineers**, v. 62, p. 259–266, 2016. Disponível em: <https://doi.org/10.1016/j.jtice.2016.02.014>

RANA, S.; DURA, H. B.; BHATTRAI, S.; SHRESTHA, R. Impact of baffle on forced convection heat transfer of CuO/water nanofluid in a micro-scale backward facing step channel. **Journal of Thermal Engineering**, v. 8, n. 3, p. 310–322, 2022. Disponível em: <https://doi.org/10.18186/thermal.1107168>

RASHIDI, M. M.; ALHUYI NAZARI, M.; MAHARIQ, I.; ALI, N. Modeling and Sensitivity Analysis of Thermal Conductivity of Ethylene Glycol-Water Based Nanofluids with Alumina Nanoparticles. **Experimental Techniques**, v. 47, n. 1, p. 83–90, 2023. Disponível em: <https://doi.org/10.1007/s40799-022-00567-4>

RIAZI, H.; MURPHY, T.; WEBBER, G. B.; ATKIN, R.; TEHRANI, S. S. M.; TAYLOR, R. A. Specific heat control of nanofluids: A critical review. **International Journal of Thermal Sciences**, v. 107, p. 25–38, 2016. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2016.03.024>

ROSEIRO, C. M. P.; CELIS, G. E. O.; LOUREIRO, J. B. R.; SILVA FREIRE, A. P. Phenomenology of bubble breakup and coalescence in sudden expansions and contractions in vertical pipes. **International Journal of Multiphase Flow**, v. 146, n. December 2020, p. 103840, 2022. Disponível em: <https://doi.org/10.1016/j.ijmultiphaseflow.2021.103840>

ROUL, M. K.; DASH, S. K. Two-phase pressure drop caused by sudden flow area contraction/expansion in small circular pipes. **International Journal for Numerical Methods in Fluids**, v. 66, n. 11, p. 1420–1446, 2011 a. Disponível em: <https://doi.org/10.1002/fld.2322>

ROUL, M. K.; DASH, S. k. Two-phase pressure drop caused by sudden flow area contraction/expansion in small circular pipes. **International Journal for Numerical Methods in Fluids**, v. 66, n. 11, p. 1420–1446, 2011 b. Disponível em: <https://doi.org/10.1002/fld.2322>

ROY, V.; MAJUMDER, S.; SANYAL, D. Analysis of the Turbulent Fluid Flow in an Axisymmetric Sudden Expansion. **International Journal of Engineering Science and Technology**, v. 2, n. 6, p. 1569–1574, 2010.

SAFAEI, M. R. **NUMERICAL AND EXPERIMENTAL STUDIES OF CONVECTION HEAT TRANSFER TO NANOFLUIDS IN CLOSED CONDUIT FLOW**. 2015. THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MECHANICAL ENGINEERING - UNIVERSITY OF MALAYA, KUALA LUMPUR, 2015.

SAFAEI, M. R.; ABDELGHANY ELKOTB, M.; ALSHARIF, A. M.; MANSIR, I. B.; ALAMRI, S.; TIRTH, V.; GOODARZI, M. An innovative design of a high strength and low weight sudden micro expansion by considering a nanofluid: Electronic cooling application. **Case Studies in Thermal Engineering**, v. 28, n. September, p. 101637, 2021 a. Disponível em: <https://doi.org/10.1016/j.csite.2021.101637>

SAFAEI, M. R.; ABDELGHANY ELKOTB, M.; ALSHARIF, A. M.; MANSIR, I. B.; ALAMRI, S.; TIRTH, V.; GOODARZI, M. An innovative design of a high strength and low weight sudden micro expansion by considering a nanofluid: Electronic cooling application. **Case Studies in Thermal Engineering**, v. 28, p. 101637, 2021 b. Disponível em: <https://doi.org/10.1016/j.csite.2021.101637>

SAFAEI, M. R.; TOGUN, H.; VAFAI, K.; KAZI, S. N.; BADARUDIN, A. Investigation of heat transfer enhancement in a forward-facing contracting channel using FMWCNT nanofluids. **Numerical Heat Transfer; Part A: Applications**, v. 66, n. 12, p. 1321–1340, 2014. Disponível em: <https://doi.org/10.1080/10407782.2014.916101>

SAHA, S.; NARAYAN DAS, A. Hydrothermal analysis of water-Al₂O₃ nanofluid flow through a sudden expansion channel with intermediate step. **Kuwait Journal of Science**, 2022. Disponível em: <https://doi.org/10.48129/kjs.15461>

SAHALUDDIN, M.; ALADE, I. O.; OYEDEJI, M. O.; ALIYU, U. S. A machine learning-based model to estimate the density of nanofluids of nitrides in ethylene glycol. **Journal of Applied Physics**, v. 127, n. 20, 2020. Disponível em: <https://doi.org/10.1063/5.0002753>

SAID, Z.; SAIDUR, R. Thermophysical Properties of Metal Oxides Nanofluids. *In: Nanofluid Heat and Mass Transfer in Engineering Problems. [S. l.]: InTech, 2017.* Disponível em: <https://doi.org/10.5772/65610>

SAID, Z.; SUNDAR, L. S.; TIWARI, A. K.; ALI, H. M.; SHEIKHOESLAMI, M.; BELLOS, E.; BABAR, H. Recent advances on the fundamental physical phenomena behind stability, dynamic motion, thermophysical properties, heat transport, applications, and challenges of nanofluids. **Physics Reports**, v. 946, p. 1–94, 2022. Disponível em: <https://doi.org/10.1016/j.physrep.2021.07.002>

SAIDINA, D. S.; ABDULLAH, M. Z.; HUSSIN, M. Metal oxide nanofluids in electronic cooling: a review. **Journal of Materials Science: Materials in Electronics**, v. 31, n. 6, p. 4381–4398, 2020. Disponível em: <https://doi.org/10.1007/s10854-020-03020-7>

SAJID, M. U.; ALI, H. M. Recent advances in application of nanofluids in heat transfer devices: A critical review. **Renewable and Sustainable Energy Reviews**, v. 103, p. 556–592, 2019. Disponível em: <https://doi.org/10.1016/j.rser.2018.12.057>

SALEH, B.; SUNDAR, L. S. Experimental study on heat transfer, friction factor, entropy and exergy efficiency analyses of a corrugated plate heat exchanger using Ni/water nanofluids. **International Journal of Thermal Sciences**, v. 165, p. 106935, 2021. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2021.106935>

SALMAN, S.; TALIB, A. R. A.; SAADON, S.; SULTAN, M. T. H. Hybrid nanofluid flow and heat transfer over backward and forward steps: A review. **Powder Technology**, v. 363, p. 448–472, 2020. Disponível em: <https://doi.org/10.1016/j.powtec.2019.12.038>

SANTOSH CHRISTOPHER, D.; KANNA, P. R.; MADHUSUDHANA, G. R.; VENKUMAR, P.; MOHAMMED, H. A. Numerical investigation of heat transfer from a two-dimensional sudden expansion flow using nanofluids. **Numerical Heat Transfer; Part A: Applications**, v. 61, n. 7, p. 527–546, 2012. Disponível em: <https://doi.org/10.1080/10407782.2012.666933>

SCHWARTZ, L. M.; GARBOCZI, E. J.; BENTZ, D. P. Interfacial transport in porous media: Application to dc electrical conductivity of mortars. **Journal of Applied Physics**, v. 78, n. 10, p. 5898–5908, 1995. Disponível em: <https://doi.org/10.1063/1.360591>

SEAWRAM, S.; NIMMANTERDWONG, P.; SEMA, T.; PIEMJAISWANG, R.; CHALERMSINSUWAN, B. Specific heat capacity prediction of hybrid nanofluid using artificial neural network and its heat transfer application. **Energy Reports**, v. 8, p. 8–15, 2022. Disponível em: <https://doi.org/10.1016/j.egyr.2022.10.238>

SELIMEFENDIGIL, F.; ÖZTOP, H. F. Effects of local curvature and magnetic field on forced convection in a layered partly porous channel with area expansion. **International Journal of Mechanical Sciences**, v. 179, n. March, 2020. Disponível em: <https://doi.org/10.1016/j.ijmecsci.2020.105696>

SELIMEFENDIGIL, F.; ÖZTOP, H. F.; ÖZGUL, R. Turbulent forced convection of nanofluid in an elliptic cross-sectional pipe. **International Communications in Heat and Mass Transfer**, v. 109, p. 104384, 2019. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2019.104384>

SELVAKUMAR, R. D.; WU, J. A comprehensive model for effective density of nanofluids based on particle clustering and interfacial layer formation. **Journal of Molecular Liquids**, v. 292, p. 111415, 2019. Disponível em: <https://doi.org/10.1016/j.molliq.2019.111415>

SELVARAJOO, K.; WANATASANAPPAN, V. V.; LUON, N. Y. Experimental measurement of thermal conductivity and viscosity of Al₂O₃-GO (80:20) hybrid and mono nanofluids: A new correlation. **Diamond and Related Materials**, v. 144, p. 111018, 2024. Disponível em: <https://doi.org/10.1016/j.diamond.2024.111018>

SETIA, H.; GUPTA, R.; WANCHOO, R. K. Stability of Nanofluids. **Materials Science Forum**, v. 757, p. 139–149, 2013. Disponível em: <https://doi.org/10.4028/www.scientific.net/MSF.757.139>

SEZER, N.; ATIEH, M. A.; KOÇ, M. A comprehensive review on synthesis, stability, thermophysical properties, and characterization of nanofluids. **Powder Technology**, v. 344, p. 404–431, 2019. Disponível em: <https://doi.org/10.1016/j.powtec.2018.12.016>

SHAHRUL, I. M.; MAHBUBUL, I. M.; KHALEDUZZAMAN, S. S.; SAIDUR, R.; SABRI, M. F. M. A comparative review on the specific heat of nanofluids for energy perspective. **Renewable and Sustainable Energy Reviews**, v. 38, p. 88–98, 2014. Disponível em: <https://doi.org/10.1016/j.rser.2014.05.081>

SHAHZAD, A.; LIAQAT, F.; ELLAHI, Z.; SOHAIL, M.; AYUB, M.; ALI, M. R. Thin film flow and heat transfer of Cu-nanofluids with slip and convective boundary condition over a stretching sheet. **Scientific Reports**, v. 12, n. 1, p. 14254, 2022. Disponível em: <https://doi.org/10.1038/s41598-022-18049-3>

SHARIFPUR, M.; YOUSEFI, S.; MEYER, J. P. A new model for density of nanofluids including nanolayer. **International Communications in Heat and Mass Transfer**, v. 78, p. 168–174, 2016. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2016.09.010>

SHI, W.; LI, F.; LIN, Q.; FANG, G.; CHEN, L.; ZHANG, L. **Experimental study on instability of round nanofluid jets at low velocity**. [S. l.: s. n.] Disponível em: <https://doi.org/10.1016/j.expthermflusci.2020.110253>

SHUKLA, K. N.; KOLLER, T. M.; RAUSCH, M. H.; FRÖBA, A. P. Effective thermal conductivity of nanofluids – A new model taking into consideration Brownian motion. **International Journal of Heat and Mass Transfer**, v. 99, p. 532–540, 2016. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2016.03.129>

SIEDER, E. N.; TATE, G. E. Heat Transfer and Pressure Drop of Liquids in Tubes. **Industrial & Engineering Chemistry**, v. 28, n. 12, p. 1429–1435, 1936. Disponível em: <https://doi.org/10.1021/ie50324a027>

SIMPSON, S.; SCHELFHOUT, A.; GOLDEN, C.; VAFAEI, S. Nanofluid Thermal Conductivity and Effective Parameters. **Applied Sciences**, v. 9, n. 1, p. 87, 2018. Disponível em: <https://doi.org/10.3390/app9010087>

SONG, X.; MA, J.; LI, Y.; SUN, X.; ZHAO, Y. Analysis of the flow phenomenon of fluid undergoing a sudden contraction to an annular gap. **Physics of Fluids**, v. 35, n. 9, 2023. Disponível em: <https://doi.org/10.1063/5.0169034>

STANDARD, A. Standard 33-78, Method of testing forced circulation air cooling and air heating coils. **American Society of Heating, Refrigerating and Air-Conditioning Engineers**, 1978.

SUGANTHI, K. S.; RAJAN, K. S. Metal oxide nanofluids: Review of formulation, thermo-physical properties, mechanisms, and heat transfer performance. **Renewable and Sustainable Energy Reviews**, v. 76, p. 226–255, 2017. Disponível em: <https://doi.org/10.1016/j.rser.2017.03.043>

SUJITH, S. V.; KIM, H.; LEE, J. A Review on Thermophysical Property Assessment of Metal Oxide-Based Nanofluids: Industrial Perspectives. **Metals**, v. 12, n. 1, p. 165, 2022. Disponível em: <https://doi.org/10.3390/met12010165>

SUN, M. H.; ZHANG, X. R. Non-Newtonian nanofluid in a micro planar sudden expansion considering variable properties. **International Journal of Thermal Sciences**, v. 107, p. 316–329, 2016. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2016.03.018>

SUN, Y.; YANG, D.; SHI, L.; WU, H.; CAO, Y.; HE, Y.; XIE, T. Properties of Nanofluids and Their Applications in Enhanced Oil Recovery: A Comprehensive Review. **Energy & Fuels**, v. 34, n. 2, p. 1202–1218, 2020. Disponível em: <https://doi.org/10.1021/acs.energyfuels.9b03501>

SUNDAR, L. S.; SHAIK, F. Heat transfer and exergy efficiency analysis of 60% water and 40% ethylene glycol mixture diamond nanofluids flow through a shell and helical coil heat exchanger. **International Journal of Thermal Sciences**, v. 184, p. 107901, 2023. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2022.107901>

SURESH, S.; VENKITARAJ, K. P.; SELVAKUMAR, P.; CHANDRASEKAR, M. Synthesis of Al₂O₃–Cu/water hybrid nanofluids using two step method and its thermo physical properties. **Colloids and Surfaces A: Physicochemical and Engineering Aspects**, v. 388, n. 1–3, p. 41–48, 2011. Disponível em: <https://doi.org/10.1016/j.colsurfa.2011.08.005>

SWINEHART, D. F. The Beer-Lambert Law. **Journal of Chemical Education**, v. 39, n. 7, p. 333, 1962. Disponível em: <https://doi.org/10.1021/ed039p333>

TAWFIK, M. M. Experimental studies of nanofluid thermal conductivity enhancement and applications: A review. **Renewable and Sustainable Energy Reviews**, v. 75, p. 1239–1253, 2017. Disponível em: <https://doi.org/10.1016/j.rser.2016.11.111>

TEKIR, M.; TASKESSEN, E.; GEDIK, E.; ARSLAN, K.; AKSU, B. Effect of constant magnetic field on Fe₃O₄–Cu/water hybrid nanofluid flow in a circular pipe. **Heat and Mass Transfer**, v. 58, n. 5, p. 707–717, 2022. Disponível em: <https://doi.org/10.1007/s00231-021-03125-7>

TENG, T.-P.; YU, C.-C. Heat dissipation performance of MWCNTs nano-coolant for vehicle. **Experimental Thermal and Fluid Science**, v. 49, p. 22–30, 2013. Disponível em: <https://doi.org/10.1016/j.expthermflusci.2013.03.007>

TIMOFEEVA, E. V.; GAVRILOV, A. N.; MCCLOSKEY, J. M.; TOLMACHEV, Y. V.; SPRUNT, S.; LOPATINA, L. M.; SELINGER, J. V. Thermal conductivity and particle

agglomeration in alumina nanofluids: Experiment and theory. **Physical Review E**, v. 76, n. 6, p. 061203, 2007. Disponível em: <https://doi.org/10.1103/PhysRevE.76.061203>

TOGUN ABDULLAH, H. **EXPERIMENTAL AND NUMERICAL STUDY OF HEAT TRANSFER TO NANOFLUID FLOW IN SUDDEN ENLARGEMENT OF ANNULAR CONCENTRIC PIPE**. Kuala Lumpur: [s. n.], 2015. Disponível em: <http://studentsrepo.um.edu.my/id/eprint/7719>. Acesso em: 27 jan. 2022.

TOGUN, H. Laminar CuO–water nano-fluid flow and heat transfer in a backward-facing step with and without obstacle. **Applied Nanoscience (Switzerland)**, v. 6, n. 3, p. 371–378, 2016. Disponível em: <https://doi.org/10.1007/s13204-015-0441-7>

TOGUN, H. 3D Numerical simulation of turbulent heat transfer and Fe_3O_4 /nanofluid annular flow in sudden enlargement. **E3S Web of Conferences**, v. 321, p. 04014, 2021. Disponível em: <https://doi.org/10.1051/e3sconf/202132104014>

TOGUN, H.; ABDULRAZZAQ, T.; KAZI, S. N.; BADARUDIN, A. Augmented of turbulent heat transfer in an annular pipe with abrupt expansion. **Thermal Science**, v. 20, n. 5, p. 1621–1632, 2016 a. Disponível em: <https://doi.org/10.2298/TSCI140816138T>

TOGUN, H.; ABDULRAZZAQ, T.; KAZI, S. N.; BADARUDIN, A.; ARIFFIN, M. K. A. Heat Transfer to Laminar Flow over a Double Backward-Facing Step. **World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering**, v. 7, p. 1742–1747, 2013 a.

TOGUN, H.; ABDULRAZZAQ, T.; KAZI, S. N.; BADARUDIN, A.; ARIFFIN, M. K. A. Numerical study of turbulent heat transfer in annular pipe with sudden contraction. **Applied Mechanics and Materials**, v. 465–466, p. 461–466, 2014 a. Disponível em: <https://doi.org/10.4028/www.scientific.net/AMM.465-466.461>

TOGUN, H.; ABDULRAZZAQ, T.; KAZI, S. N.; BADARUDIN, A.; ARIFFIN, M. K. A.; ZUBIR, M. N. M. Numerical Study of Heat Transfer and Laminar Flow over a Backward Facing Step with and without Obstacle. **International Journal of Aerospace and Mechanical Engineering**, v. 8, p. 363–367, 2014 b.

TOGUN, H.; ABDULRAZZAQ, T.; KAZI, S. N.; BADARUDIN, A.; KADHUM, A. A. H.; SADEGHINEZHAD, E. A review of studies on forced, natural and mixed heat transfer to fluid and nanofluid flow in an annular passage. **Renewable and Sustainable Energy Reviews**, v. 39, p. 835–856, 2014 c. Disponível em: <https://doi.org/10.1016/j.rser.2014.07.008>

TOGUN, H.; ABU-MULAWEH, H. I.; KAZI, S. N.; BADARUDIN, A. Numerical simulation of heat transfer and separation Al₂O₃/nanofluid flow in concentric annular pipe. **International Communications in Heat and Mass Transfer**, v. 71, p. 108–117, 2016 b. Disponível em: <https://doi.org/10.1016/j.icheatmasstransfer.2015.12.014>

TOGUN, H.; AHMADI, G.; ABDULRAZZAQ, T.; SHKARAH, A. J.; KAZI, S. N.; BADARUDIN, A.; SAFAEI, M. R. Thermal performance of nanofluid in ducts with double forward-facing steps. **Journal of the Taiwan Institute of Chemical Engineers**, v. 47, p. 28–42, 2015. Disponível em: <https://doi.org/10.1016/j.jtice.2014.10.009>

TOGUN, H.; BEN HAMIDA, M. B.; HUSSEIN, A. K.; ABED, A. M.; HASAN, H. A.; HOMOD, R. Z.; ABDULRAZZAQ, T.; YASEEN, Z. M.; BISWAS, N.; ALHASSAN, M. S. Heat transfer and fluid flow characteristics over a backward-facing step (BFS) containing square-rectangular ribs integrated as forward-facing steps (FFS). **Journal of Thermal Analysis and Calorimetry**, v. 149, n. 7, p. 3043–3057, 2024. Disponível em: <https://doi.org/10.1007/s10973-024-12879-1>

TOGUN, H.; HAMIDATOU, S.; MOHAMMED, H. I.; ABED, Azher. M.; HASAN, H. A.; HOMOD, R. Z.; AL-FATLAWI, A. W.; AL-THAMIR, M.; ABDULRAZZAQ, T. Numerical Simulation on Heat Transfer Augmentation by Using Innovative Hybrid Ribs in a Forward-Facing Contracting Channel. **Symmetry**, v. 15, n. 3, p. 690, 2023 a. Disponível em: <https://doi.org/10.3390/sym15030690>

TOGUN, H.; HOMOD, R.; ABDULRAZZAQ, T. Hybrid Al₂O₃-Cu/water nanofluid flow and heat transfer over vertical double forward-facing step. **Thermal Science**, v. 25, n. 5 Part A, p. 3517–3529, 2021. Disponível em: <https://doi.org/10.2298/TSCI201130080T>

TOGUN, H.; KAZI, S. N.; BADARUDIN, A. Turbulent heat transfer to separation nanofluid flow in annular concentric pipe. **International Journal of Thermal Sciences**, v. 117, p. 14–25, 2017. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2017.03.014>

TOGUN, H.; S SULTAN, H.; HAMIDATOU, S.; I MOHAMMED, H.; Z HOMOD, R.; ALHASSAN, M. S.; M DHABAB, J.; SADEQ, A. M.; YASEEN, Z. M.; DEGHOUM, K.; HADJAD, A. Comparative study on heat transfer improvement of nanofluids flow in forward-facing reducing channel with and without novel hybrid ribs. **International Journal of Thermal Sciences**, v. 193, p. 108543, 2023 b. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2023.108543>

TOGUN, H.; S SULTAN, H.; HAMIDATOU, S.; I MOHAMMED, H.; Z HOMOD, R.; ALHASSAN, M. S.; M DHABAB, J.; SADEQ, A. M.; YASEEN, Z. M.; DEGHOUM, K.; HADJAD, A. Comparative study on heat transfer improvement of nanofluids flow in forward-facing reducing channel with and without novel hybrid ribs. **International Journal of Thermal Sciences**, v. 193, p. 108543, 2023 c. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2023.108543>

TOGUN, H.; SAFAEI, M. R.; SADRI, R.; KAZI, S. N.; BADARUDIN, A.; HOOMAN, K.; SADEGHINEZHAD, E. Numerical simulation of laminar to turbulent nanofluid flow and heat transfer over a backward-facing step. **Applied Mathematics and Computation**, v. 239, p. 153–170, 2014 d. Disponível em: <https://doi.org/10.1016/j.amc.2014.04.051>

TOGUN, H.; SALMAN, Y. K.; SULTAN ALJIBORI, H. S.; KAZI, S. N. **An experimental study of heat transfer to turbulent separation fluid flow in an annular passage.** [S. l.: s. n.] Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2010.10.031>

TOGUN, H.; SHKARAH, A. J.; KAZI, S. N.; BADARUDIN, A. CFD Simulation of Heat Transfer and Turbulent Fluid Flow over a Double Forward-Facing Step. **Mathematical Problems in Engineering**, v. 2013, p. 1–10, 2013 b. Disponível em: <https://doi.org/10.1155/2013/895374>

TUOK, L. P.; ELKADY, M.; ZKRIA, A.; YOSHITAKE, T.; NOUR ELDEMERDASH, U. Evaluation of stability and functionality of zinc oxide nanofluids for enhanced oil recovery. **Micro and Nano Systems Letters**, v. 11, n. 1, p. 12, 2023. Disponível em: <https://doi.org/10.1186/s40486-023-00180-z>

UDAWATTHA, D. S.; NARAYANA, M.; WIJAYARATHNE, U. P. L. Predicting the effective viscosity of nanofluids based on the rheology of suspensions of solid particles.

Journal of King Saud University - Science, v. 31, n. 3, p. 412–426, 2019. Disponível em: <https://doi.org/10.1016/j.jksus.2017.09.016>

VAJJHA, R. S.; DAS, D. K. Specific Heat Measurement of Three Nanofluids and Development of New Correlations. **Journal of Heat Transfer**, v. 131, n. 7, 2009. Disponível em: <https://doi.org/10.1115/1.3090813>

VAKA, M.; WALVEKAR, R. An experimental study on thermal efficiency of hybrid GO/MWCNTs nanoparticles suspended in a binary mixture of ethylene glycol and water. **Materials Today: Proceedings**, v. 73, p. 354–360, 2023. Disponível em: <https://doi.org/10.1016/j.matpr.2022.11.127>

VIDYA, B.; JOHNSON, A. P.; HRISHIKESH, G.; JYOTHI, S. L.; KUMAR, S. H.; PRAMOD, K.; GANGADHARAPPA, H. V. Biomedical applications of carbon nanotubes. *In: Fiber and Textile Engineering in Drug Delivery Systems*. [S. l.]: Elsevier, 2023. p. 127–167. Disponível em: <https://doi.org/10.1016/B978-0-323-96117-2.00015-7>

WANG, J.; YANG, X.; KLEMEŠ, J. J.; TIAN, K.; MA, T.; SUNDEN, B. A review on nanofluid stability: preparation and application. **Renewable and Sustainable Energy Reviews**, v. 188, p. 113854, 2023. Disponível em: <https://doi.org/10.1016/j.rser.2023.113854>

WANG, W.; ZHANG, Y.; LI, B.; HAN, H.; GAO, X. Influence of geometrical parameters on turbulent flow and heat transfer characteristics in outward helically corrugated tubes. **Energy Conversion and Management**, v. 136, p. 294–306, 2017. Disponível em: <https://doi.org/10.1016/j.enconman.2017.01.029>

WANG, X.; XU, X.; CHOI, S. U. S. Thermal Conductivity of Nanoparticle - Fluid Mixture. **Journal of Thermophysics and Heat Transfer**, v. 13, n. 4, p. 474–480, 1999. Disponível em: <https://doi.org/10.2514/2.6486>

WANG, X.-Q.; MUJUMDAR, A. S. Heat transfer characteristics of nanofluids: a review. **International Journal of Thermal Sciences**, v. 46, n. 1, p. 1–19, 2007. Disponível em: <https://doi.org/10.1016/j.ijthermalsci.2006.06.010>

WOHL, J.; BECK, J.; INMAN, K.; PALMER, M.; CUMMINGS, M.; FULMER, R.; VAFAEI, S. Hybrid Nanofluid Thermal Conductivity and Optimization: Original Approach

and Background. **Nanomaterials**, v. 12, n. 16, p. 2847, 2022. Disponível em: <https://doi.org/10.3390/nano12162847>

WONG, M. K.; SHENG, L. C.; AZWADI, C. S. N.; HASHIM, G. A. **Numerical Study of Turbulent Flow in Pipe with Sudden Expansion** **Journal of Advanced Research in Fluid Mechanics and Thermal Sciences** ISSN. [S. l.: s. n.].

WONG, K. V.; CASTILLO, M. J. Heat Transfer Mechanisms and Clustering in Nanofluids. **Advances in Mechanical Engineering**, v. 2, p. 795478, 2010. Disponível em: <https://doi.org/10.1155/2010/795478>

WU, W.-C.; KUMAR, A. Numerical Investigation of Nanofluid Flow over a Backward Facing Step. **Aerospace**, v. 9, n. 9, p. 499, 2022. Disponível em: <https://doi.org/10.3390/aerospace9090499>

XIE, H.; LEE, H.; YOUN, W.; CHOI, M. Nanofluids containing multiwalled carbon nanotubes and their enhanced thermal conductivities. **Journal of Applied Physics**, v. 94, n. 8, p. 4967, 2003. Disponível em: <https://doi.org/10.1063/1.1613374>

XIE, W. A.; XI, G. N. Caractéristiques d'écoulement de fluide et de transfert de chaleur d'un écoulement de séparation et de réattachement en marche arrière. **International Journal of Refrigeration**, v. 74, p. 175–187, 2017. Disponível em: <https://doi.org/10.1016/j.ijrefrig.2016.10.006>

XUAN, Y.; ROETZEL, W. Conceptions for heat transfer correlation of nanofluids. **International Journal of Heat and Mass Transfer**, v. 43, n. 19, p. 3701–3707, 2000. Disponível em: [https://doi.org/10.1016/S0017-9310\(99\)00369-5](https://doi.org/10.1016/S0017-9310(99)00369-5)

YADAV, D.; NIRALA, A.; KUMAR, R.; KUMAR SINGH, P. Density variation in nanofluids as a function of concentration and temperature. **Materials Today: Proceedings**, v. 46, p. 6576–6580, 2021. Disponível em: <https://doi.org/10.1016/j.matpr.2021.04.052>

YANG, D.; SUN, B.; XU, T.; LIU, B.; LI, H. Experimental and numerical study on the flow and heat transfer characteristic of nanofluid in the recirculation zone of backward-facing step microchannels. **Applied Thermal Engineering**, v. 199, n. September, p. 117527, 2021. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2021.117527>

YANG, L.; JI, W.; MAO, M.; HUANG, J. An updated review on the properties, fabrication and application of hybrid-nanofluids along with their environmental effects. **Journal of Cleaner Production**, v. 257, p. 120408, 2020. Disponível em: <https://doi.org/10.1016/j.jclepro.2020.120408>

YANG, Y.; OZTEKIN, A.; NETI, S.; MOHAPATRA, S. Particle agglomeration and properties of nanofluids. **Journal of Nanoparticle Research**, v. 14, n. 5, p. 852, 2012. Disponível em: <https://doi.org/10.1007/s11051-012-0852-2>

YASMIN, H.; GIWA, S. O.; NOOR, S.; SHARIFPUR, M. Thermal Conductivity Enhancement of Metal Oxide Nanofluids: A Critical Review. **Nanomaterials**, v. 13, n. 3, p. 597, 2023. Disponível em: <https://doi.org/10.3390/nano13030597>

YOUNES, H.; MAO, M.; SOHEL MURSHED, S. M.; LOU, D.; HONG, H.; PETERSON, G. P. Nanofluids: Key parameters to enhance thermal conductivity and its applications. **Applied Thermal Engineering**, v. 207, p. 118202, 2022 a. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2022.118202>

YOUNES, H.; MAO, M.; SOHEL MURSHED, S. M.; LOU, D.; HONG, H.; PETERSON, G. P. Nanofluids: Key parameters to enhance thermal conductivity and its applications. **Applied Thermal Engineering**, v. 207, p. 118202, 2022 b. Disponível em: <https://doi.org/10.1016/j.applthermaleng.2022.118202>

YOUSEFI, F.; AMOOZANDEH, Z. A new model to predict the densities of nanofluids using statistical mechanics and artificial intelligent plus principal component analysis. **Chinese Journal of Chemical Engineering**, v. 25, n. 9, p. 1273–1281, 2017. Disponível em: <https://doi.org/10.1016/j.cjche.2016.10.016>

YOUSEFI, F.; KAVEH, M. Tao-Mason equation of state for refractory metals. **Indian Journal of Science and Technology**, v. 5, n. 3, 2012. Disponível em: <http://www.indjst.org>

YU, F.; CHEN, Y.; LIANG, X.; XU, J.; LEE, C.; LIANG, Q.; TAO, P.; DENG, T. Dispersion stability of thermal nanofluids. **Progress in Natural Science: Materials International**, v. 27, n. 5, p. 531–542, 2017. Disponível em: <https://doi.org/10.1016/j.pnsc.2017.08.010>

YU, W.; CHOI, S. U. S. The Role of Interfacial Layers in the Enhanced Thermal Conductivity of Nanofluids: A Renovated Maxwell Model. **Journal of Nanoparticle Research**, v. 5, n. 1/2, p. 167–171, 2003 a. Disponível em: <https://doi.org/10.1023/A:1024438603801>

YU, W.; CHOI, S. U. S. The Role of Interfacial Layers in the Enhanced Thermal Conductivity of Nanofluids: A Renovated Maxwell Model. **Journal of Nanoparticle Research**, v. 5, n. 1/2, p. 167–171, 2003 b. Disponível em: <https://doi.org/10.1023/A:1024438603801>

YU, W.; CHOI, S. U. S. The Role of Interfacial Layers in the Enhanced Thermal Conductivity of Nanofluids: A Renovated Maxwell Model. **Journal of Nanoparticle Research**, v. 5, n. 1/2, p. 167–171, 2003 c. Disponível em: <https://doi.org/10.1023/A:1024438603801>

YU, W.; CHOI, S. U. S. The role of interfacial layers in the enhanced thermal conductivity of nanofluids: A renovated Hamilton-Crosser model. **Journal of Nanoparticle Research**, v. 6, n. 4, p. 355–361, 2004. Disponível em: <https://doi.org/10.1007/s11051-004-2601-7>

YU, W.; XIE, H. A review on nanofluids: Preparation, stability mechanisms, and applications. **Journal of Nanomaterials**, v. 2012, 2012. Disponível em: <https://doi.org/10.1155/2012/435873>

YU, Y.; DU, J.; HOU, J.; JIN, X.; WANG, R. Investigation into the underlying mechanisms of the improvement of thermal conductivity of the hybrid nanofluids. **International Journal of Heat and Mass Transfer**, v. 226, p. 125468, 2024. Disponível em: <https://doi.org/10.1016/j.ijheatmasstransfer.2024.125468>

ZABOUR, K.; FEDDAOUI, M.; MEFTAH, H. Effect of metal oxide nanofluids on the performance of passive solar still single slope for two different absorbent plates. **Heat Transfer**, v. 51, n. 4, p. 3675–3695, 2022. Disponível em: <https://doi.org/10.1002/htj.22470>

ZHANG, A.; WANG, Z.; DING, G.; MENG, H.; WANG, Z. Numerical and experimental investigation on heat transfer characteristics of nanofluids in a circular tube with CDTE. **Heat and Mass Transfer**, v. 57, n. 8, p. 1329–1345, 2021. Disponível em: <https://doi.org/10.1007/s00231-021-03026-9>

ZHANG, H.; FENG, Z.; LIU, X.; YIN, D. Flow and heat transfer characteristics of nanofluids in sudden expansion structure based on SLA method. **Thermal Science**, v. 23, n. 3 Part A, p. 1449–1455, 2019. Disponível em: <https://doi.org/10.2298/tsci180609210z>

ZHANG, J.; LEI, L.; LI, H.; XIN, G.; WANG, X. Experimental and numerical studies of liquid-liquid two-phase flows in microchannel with sudden expansion/contraction cavities. **Chemical Engineering Journal**, v. 433, p. 133820, 2022. Disponível em: <https://doi.org/10.1016/j.cej.2021.133820>

ZHELEZNY, V. P.; MOTOVOY, I. V; USTYUZHANIN, E. E. Prediction of nanofluids properties: the density and the heat capacity. **Journal of Physics: Conference Series**, v. 891, p. 012347, 2017. Disponível em: <https://doi.org/10.1088/1742-6596/891/1/012347>

ZHOU, L.-P.; WANG, B.-X.; PENG, X.-F.; DU, X.-Z.; YANG, Y.-P. On the Specific Heat Capacity of CuO Nanofluid. **Advances in Mechanical Engineering**, v. 2, p. 172085, 2010. Disponível em: <https://doi.org/10.1155/2010/172085>

ZHOU, S.; REN, Z.; YU, Y.; LIU, Y.; DU, H.; LV, X.; YUAN, Q. Study of Sintering Behavior of Methane Hydrate Particles on the Wall Surface. **Langmuir**, v. 40, n. 12, p. 6537–6549, 2024. Disponível em: <https://doi.org/10.1021/acs.langmuir.4c00192>

APPENDIX A

EDX spectrum analysis confirmed the presence of the main elements of the nanoparticles. Figs. (1A) to (4A) show the presence of the main element C (carbon), both in samples containing carbon nanotube (86.7 % C in MWCNT and 90.35 % C in FMWCNT), graphene samples (97.17 % C) and industrial graphene samples.

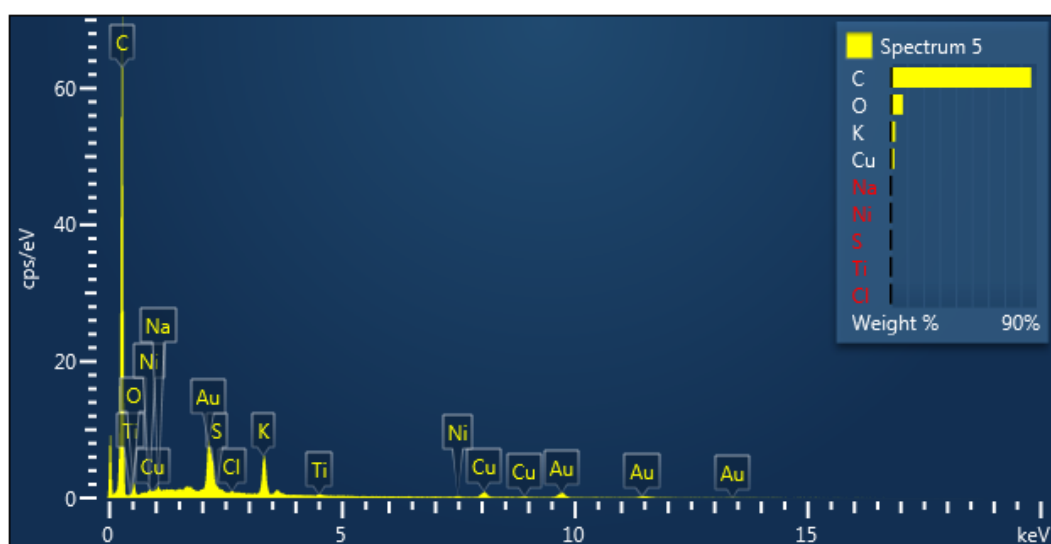


Figure 1A - EDX spectrum for MWCN nanoparticles. Source: Author's own.

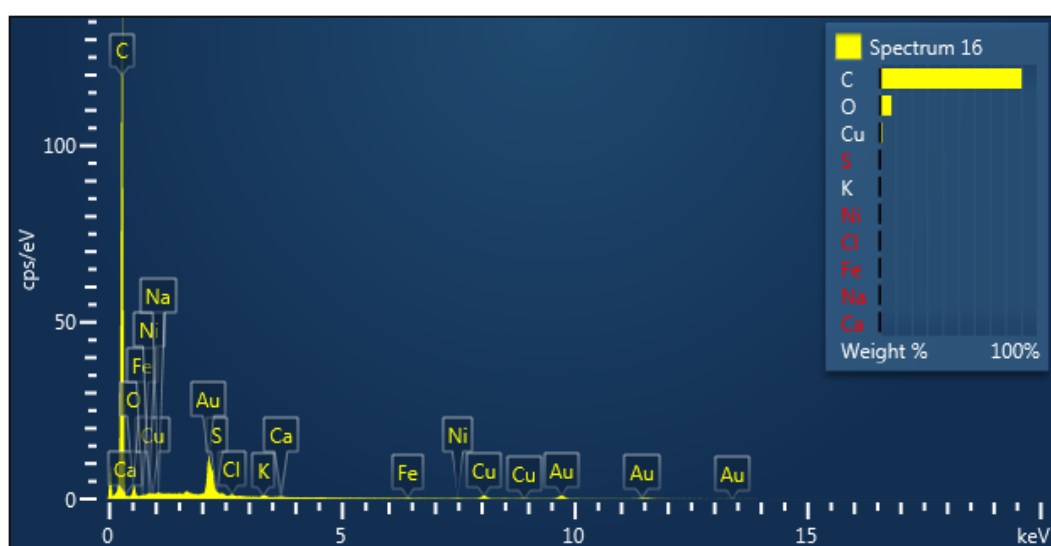


Figure 2A - EDX spectrum for FMWCN nanoparticles. Source: Author's own.

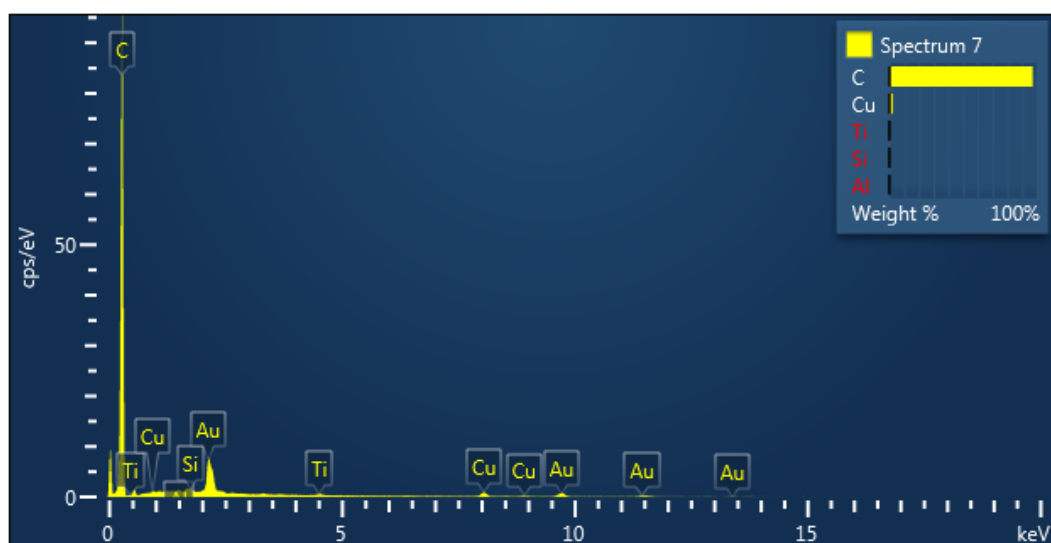


Figure 3A – EDX spectrum for graphene nanoparticles. Source Author's own.



Figure 4A – EDX spectrum for Industrial graphene nanoparticles. Source Author's own.

APPENDIX B

The T-type thermocouples were constructed by applying an electric arc discharge to the two thermocouple wires (Copper/Constantan), fusing the two metals, and creating the junction. The process was controlled by the charge-discharge of a capacitor bank.

The thermocouples were calibrated using a set of precision thermometers and a thermal bath as reference. The calibration process involved inserting the thermocouples and the precision thermometer into a thermostatic bath, as shown in Fig. (1B).



Figure 1B – Calibration process of the thermocouples. Adapted from (Cárdenas Gómez, 2019).

The signal from the thermocouples was recorded by a National Instruments data acquisition system, while the reference value was provided by a precision mercury bulb immersion thermometer with a resolution of 0.1 °C. Calibration curves for the 30 thermocouples were generated over a temperature range of 10 °C to 90 °C, with 10 °C increments. The temperature provided by the precision thermometer was considered as $T_{Standard}$.

The uncertainty associated with the measurements was based on the standard deviation presented by the linear regression of the temperature relationship. The linear regression of the curve shown in Fig. (2B) provided the following relationship:

$$T_{\text{Thermocouple}} = -0.22461 + 1.00586 \cdot T_{\text{Standard}} \quad (1B)$$

Assuming a normal distribution for the deviations, the uncertainties in the temperature measurements were ± 0.2 °C, or two times the standard deviation, with a 95 % confidence interval. This value is acceptable according to the ANSI MC96.1-1982 and ASTM E320 standards for T-type thermocouples ($E_{\text{max}} = \pm 1$ °C).

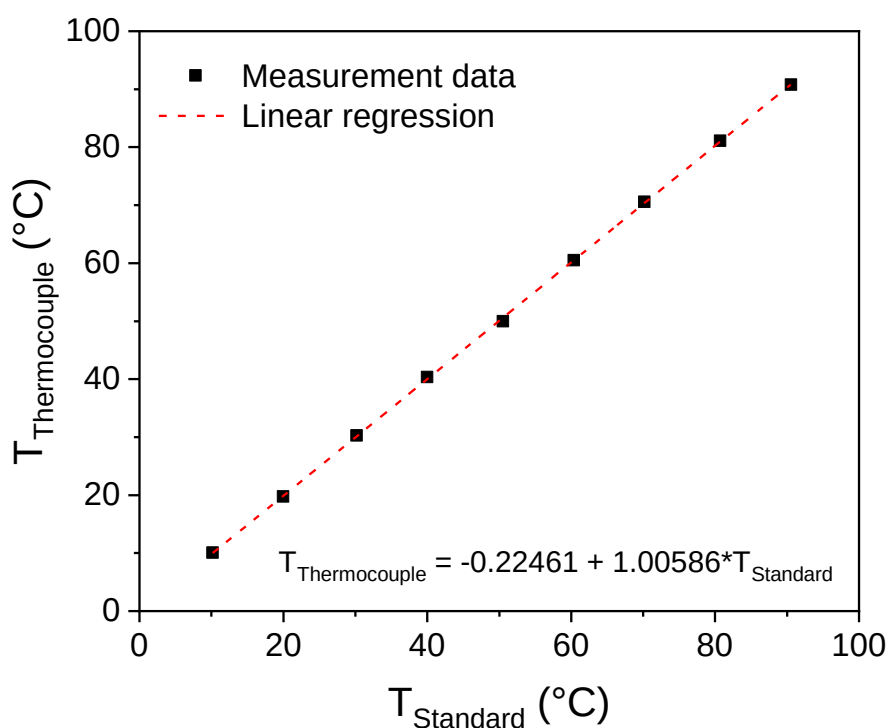
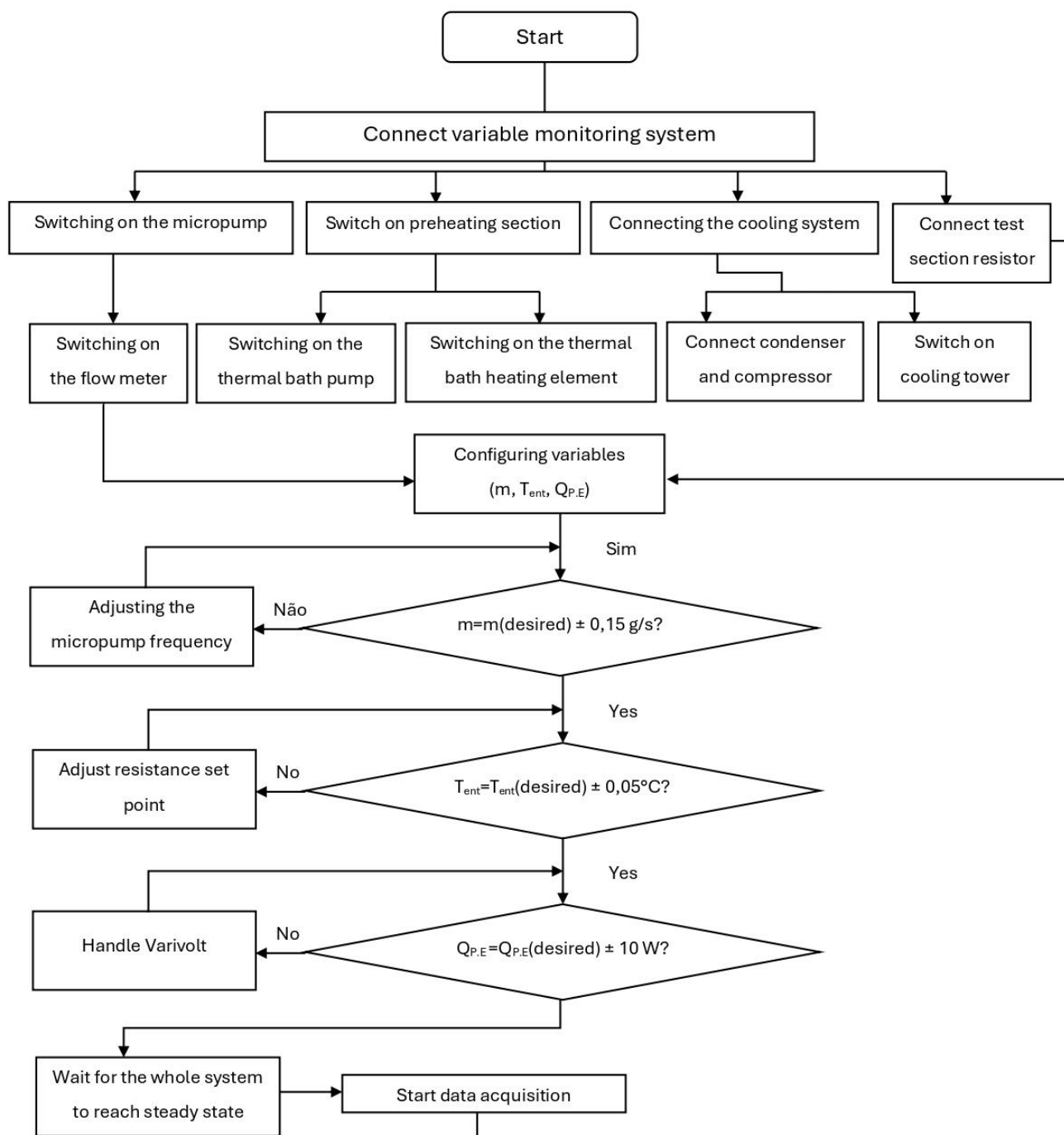
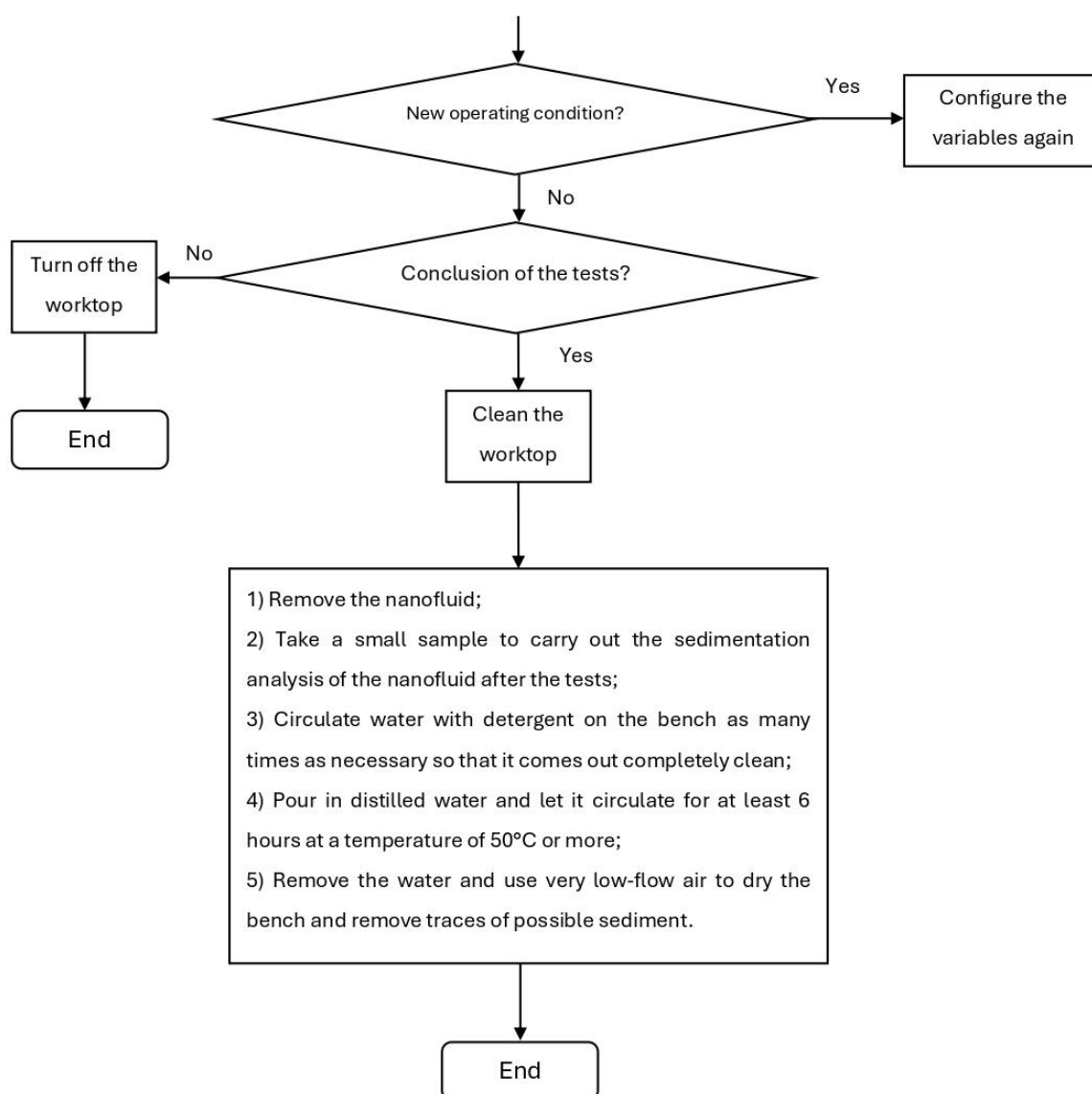


Figure 2B – Thermocouple calibration curve. Source: Author's own.

APPENDIX C





At the conclusion of each experiment, the experimental setup was thoroughly cleaned with water and neutral detergent following each test series to prevent cross-contamination in subsequent tests with different types of nanoparticles.

APPENDIX D

Fig. (1D) presents the experimental results obtained in the tests using the base fluid (H₂O:EG 50:50 % wt.) for straight pipe to verify the energy balance, $\dot{Q}_{E.B.}$. Where, $\dot{Q}_{E.P.}$, varied from 340 to 750 W. Therefore, the average deviation for the energy balance in 24 tests performed with the test fluids was less than $\pm 5\%$. Under these conditions, the thermal insulation used in the test section proved adequate to avoid significant heat losses.

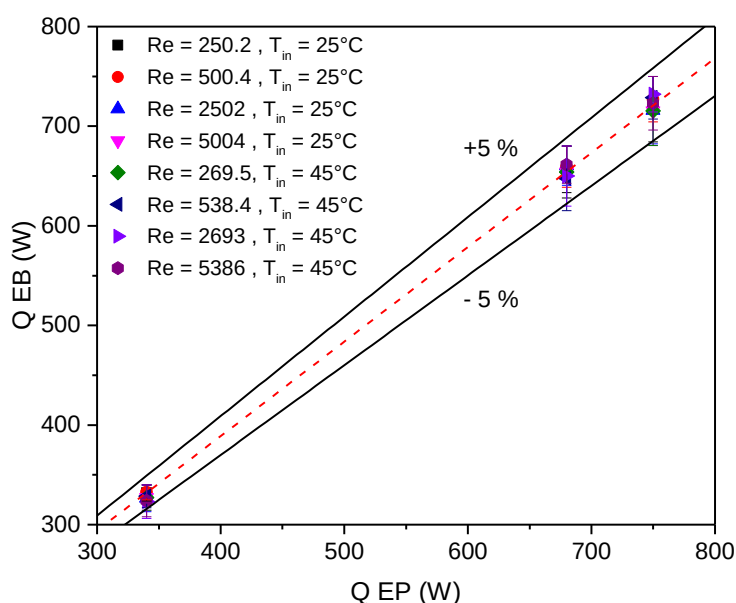


Figure 1D – Comparison of electrical power, $\dot{Q}_{E.B.}$, and the power calculated by the energy balance, $\dot{Q}_{E.P.}$, for H₂O:EG 50:50 % wt. for the straight pipe. Source: Author's own.

Fig. (2D) presents the experimental results for the test fluid friction factor were compared with the Blasius and laminar models for the straight pipe. The mean deviation obtained in the laminar regime was $\pm 20\%$. In the turbulent regime, the comparison between the Blasius model and the experimental presented a mean deviation of $\pm 3\%$. Therefore, it can be observed that the results of the flow characteristics and the fluid-dynamic behavior of the reference fluid used

in the experimental bench presented a good agreement when compared with the two models used to validate the experimental setup.

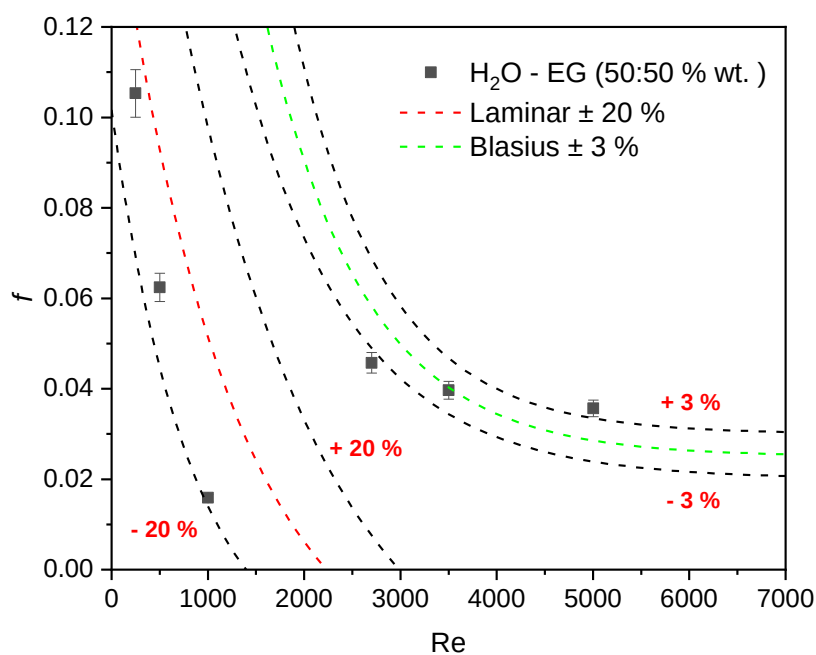


Figure 2D – Experimental friction factor as a function of Reynolds number compared with Blasius model and laminar regime for the straight pipe. Source: Author's own.

APPENDIX E

Figs. (1E) and (2E) compare the experimental Nu number for H₂O: EG with the models of (SIEDER and TATE, 1936) and (GNIELINSKI, 1975), respectively, for laminar and turbulent flows. An average mean deviation of 17 % was observed for the experimental Nusselt number with the theoretical laminar model and approximately 7 % for the turbulent model.

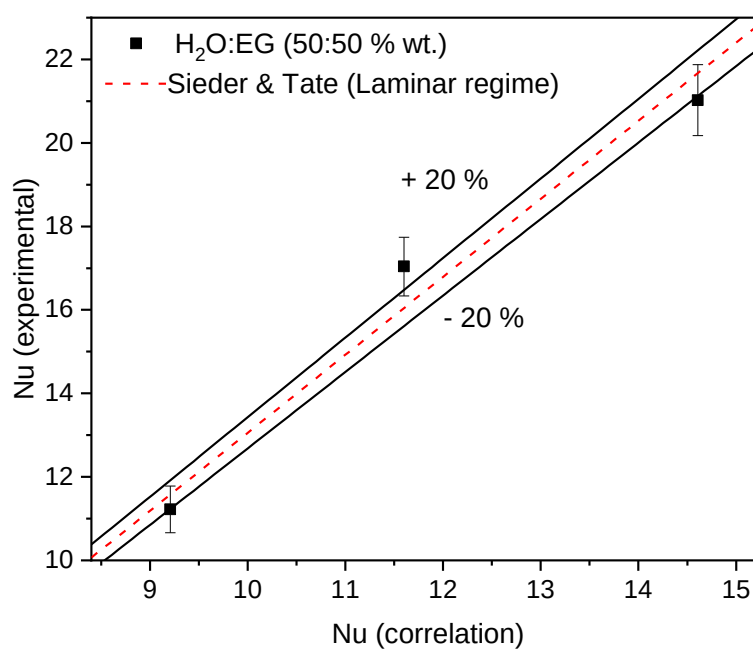


Figure 1E – Comparison between the experimental Nu and the correlation of (SIEDER and TATE, 1936). Source: Author's own.

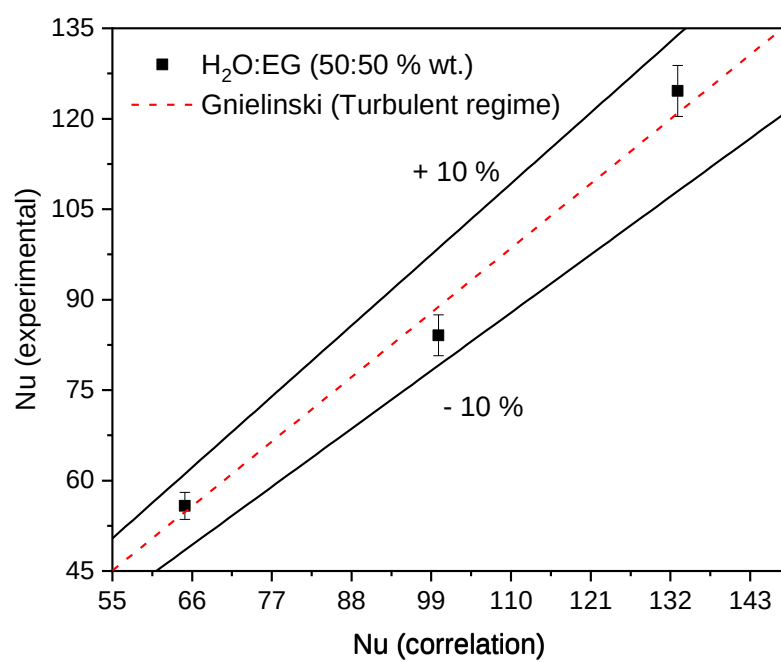


Figure 2E – Comparison between the experimental Nu and the correlation of (GNIELINSKI, 1975). Source: Author's own.

APPENDIX F

Heat transfer uncertainties

Convective heat transfer coefficient

The convective heat transfer coefficient is calculated from:

$$h(x) = \frac{q''}{T_w(x) - T_p(x)} \quad (1F)$$

with its uncertainty given by:

$$\delta h(x) = \left[\left(\frac{\partial h(x)}{\partial q''} \cdot \delta q'' \right)^2 + \left(\frac{\partial h(x)}{\partial T_w} \cdot \delta T_w \right)^2 + \left(\frac{\partial h(x)}{\partial T_p} \cdot \delta T_p \right)^2 \right]^{1/2} \quad (2F)$$

$$\delta h(x) = \left[\left(\frac{\delta q''}{T_w(x) - T_p(x)} \right)^2 + \left(\frac{-q''}{(T_w(x) - T_p(x))^2} \cdot \delta T_w \right)^2 + \left(\frac{-q''}{T_w(x) - T_p(x)} \cdot \delta T_p \right)^2 \right]^{1/2} \quad (3F)$$

The wall temperatures are measured at 31 points, and between each point the local heat transfer coefficient is calculated. The average heat transfer coefficient was obtained by adding the local convective heat transfer coefficient and then dividing the result by 30.

$$h_{avg} = \frac{1}{n} \cdot [h(x_1) + \dots + h(x_n)] \quad (4F)$$

$$\delta h_{avg} = \left[\left(\frac{\partial h_{avg}}{\partial h(x_1)} \cdot \delta h(x_1) \right)^2 + \dots + \left(\frac{\partial h_{avg}}{\partial h(x_n)} \cdot \delta h(x_n) \right)^2 \right]^{1/2} \quad (5F)$$

hence the uncertainty of the average convective heat transfer coefficient is given by:

$$\delta h_{avg} = \frac{1}{n} \cdot [h(x_1)^2 + \dots + h(x_n)^2]^{1/2} \quad (6F)$$

Heat flux

The heat flux uncertainty is calculated from:

$$\dot{Q} = V \cdot I \quad (7F)$$

with,

$$\delta \dot{Q} = \left[\left(\frac{\partial \dot{Q}}{\partial V} \cdot \delta V \right)^2 + \left(\frac{\partial \dot{Q}}{\partial I} \cdot \delta I \right)^2 \right]^{1/2} \quad (8F)$$

$$\delta \dot{Q} = [(I \cdot \delta V)^2 + (V \cdot \delta I)^2]^{1/2} \quad (9F)$$

Heat transfer area

The heat transfer area is calculated from:

$$A_s = \pi \cdot D \cdot L \quad (10F)$$

with its uncertainty given by

$$\delta A_s = \left[\left(\frac{\partial A_s}{\partial D} \cdot \delta D \right)^2 + \left(\frac{\partial A_s}{\partial L} \cdot \delta L \right)^2 \right]^{1/2} \quad (11F)$$

$$\delta A_s = [(\pi \cdot \delta D \cdot L)^2 + (\pi \cdot D \cdot \delta L)^2]^{1/2} \quad (12F)$$

Perimeter of test section

The perimeter of the test section is calculated from:

$$P = \pi \cdot D \quad (13F)$$

with its uncertainty is given by:

$$\delta P = \left[\left(\frac{\partial P}{\partial D} \cdot \delta D \right)^2 \right]^{1/2} \quad (14F)$$

$$\delta P = \pi \cdot \delta D \quad (15F)$$

Dimensionless parameters

Since all fluid flow and heat transfer equations are in terms of dimensionless parameters, the uncertainties of these parameters are determined. The Nusselt, Reynolds and Prandtl number are mainly used in the study of heat transfer and their respective uncertainties are given by:

$$Nu_{avg} = \frac{h_{avg} \cdot D}{\kappa} \quad (16F)$$

with its uncertainty given by:

$$\delta Nu_{avg} = \left[\left(\frac{\partial Nu_{avg}}{\partial h_{avg}} \cdot \delta h_{avg} \right)^2 + \left(\frac{\partial Nu_{avg}}{\partial D} \cdot \delta D \right)^2 + \left(\frac{\partial Nu_{avg}}{\partial \kappa} \cdot \delta \kappa \right)^2 \right]^{1/2} \quad (17F)$$

$$\delta Nu_{avg} = \left[\left(\frac{D}{\kappa} \cdot \delta h_{avg} \right)^2 + \left(\frac{h_{avg}}{\kappa} \cdot \delta D \right)^2 + \left(-\frac{h_{avg}}{\kappa^2} \cdot \delta \kappa \right)^2 \right]^{1/2} \quad (18F)$$

$$Re = \frac{4 \cdot \dot{m}}{\mu \cdot D \cdot \pi} \quad (19F)$$

with its uncertainty given by:

$$\delta Re = \left[\left(\frac{\partial Re}{\partial \dot{m}} \cdot \delta \dot{m} \right)^2 + \left(\frac{\partial Re}{\partial \mu} \cdot \delta \mu \right)^2 + \left(\frac{\partial Re}{\partial D} \cdot \delta D \right)^2 \right]^{1/2} \quad (20F)$$

$$\delta Re = \left[\left(\frac{4}{\mu \cdot D \cdot \pi} \right)^2 + \left(-\frac{4 \cdot \dot{m}}{\mu^2 \cdot D \cdot \pi} \right)^2 + \left(-\frac{4 \cdot \dot{m}}{\mu \cdot D^2 \cdot \pi} \right)^2 \right]^{1/2} \quad (21F)$$

$$Pr = \frac{\mu \cdot C_p}{\kappa} \quad (22F)$$

with its uncertainty given by:

$$\delta Pr = \left[\left(\frac{\partial Pr}{\partial \mu} \cdot \delta \mu \right)^2 + \left(\frac{\partial Pr}{\partial C_p} \cdot \delta C_p \right)^2 + \left(\frac{\partial Pr}{\partial \kappa} \cdot \delta \kappa \right)^2 \right]^{1/2} \quad (23F)$$

$$\delta Pr = \left[\left(\frac{C_p}{\kappa} \right)^2 + \left(\frac{\mu}{\kappa} \right)^2 + \left(-\frac{\mu \cdot C_p}{\kappa^2} \right)^2 \right]^{1/2} \quad (24F)$$

APPENDIX G

Absorbance of the nanofluids

Table 1G displays the absorbance of the nanofluid samples at the reference wavelength of 400 nm for different time periods. It is evident from the table that the mass concentration decreases over time. This phenomenon can be attributed to the settling of the samples, resulting in a gradual reduction in absorbance over time.

Table 1G – Absorbance of nanofluids containing MWCNT, FMWCNT and graphene at different measurements time.

		Mass fraction	1 h	24 h	48 h	72 h	96 h	120 h	144 h
Absorbance	MWCNT	0.005	1	0.92466	0.84664	0.7654	0.71497	0.66544	0.63006
		0.01	1	0.8872	0.75036	0.63191	0.53161	0.48645	0.45003
		0.05	1	0.855	0.42691	0.22814	0.18958	0.15401	0.12778
	FMWCNT	0.005	1	0.97951	0.96165	0.92264	0.92052	0.91419	0.86508
		0.01	1	0.99312	0.98856	0.97501	0.95065	0.94411	0.90176
		0.05	1	0.99084	0.93331	0.92264	0.9163	0.90166	0.8893
	Graphene	0.01	1	0.85152	0.81904	0.71086	0.60303	0.36869	0.25758
		0.05	1	0.80442	0.7702	0.62753	0.45707	0.27146	0.16414
	Industrial graphene	0.01	1	0.96042	0.81266	0.63588	0.48549	0.35303	0.26649
		0.05	1	0.92549	0.72427	0.49011	0.30858	0.11478	0.02507

Source: Author's own.

APPENDIX H

Overall heat transfer enhancements for all nanofluid samples analyzed for the straight pipe case.

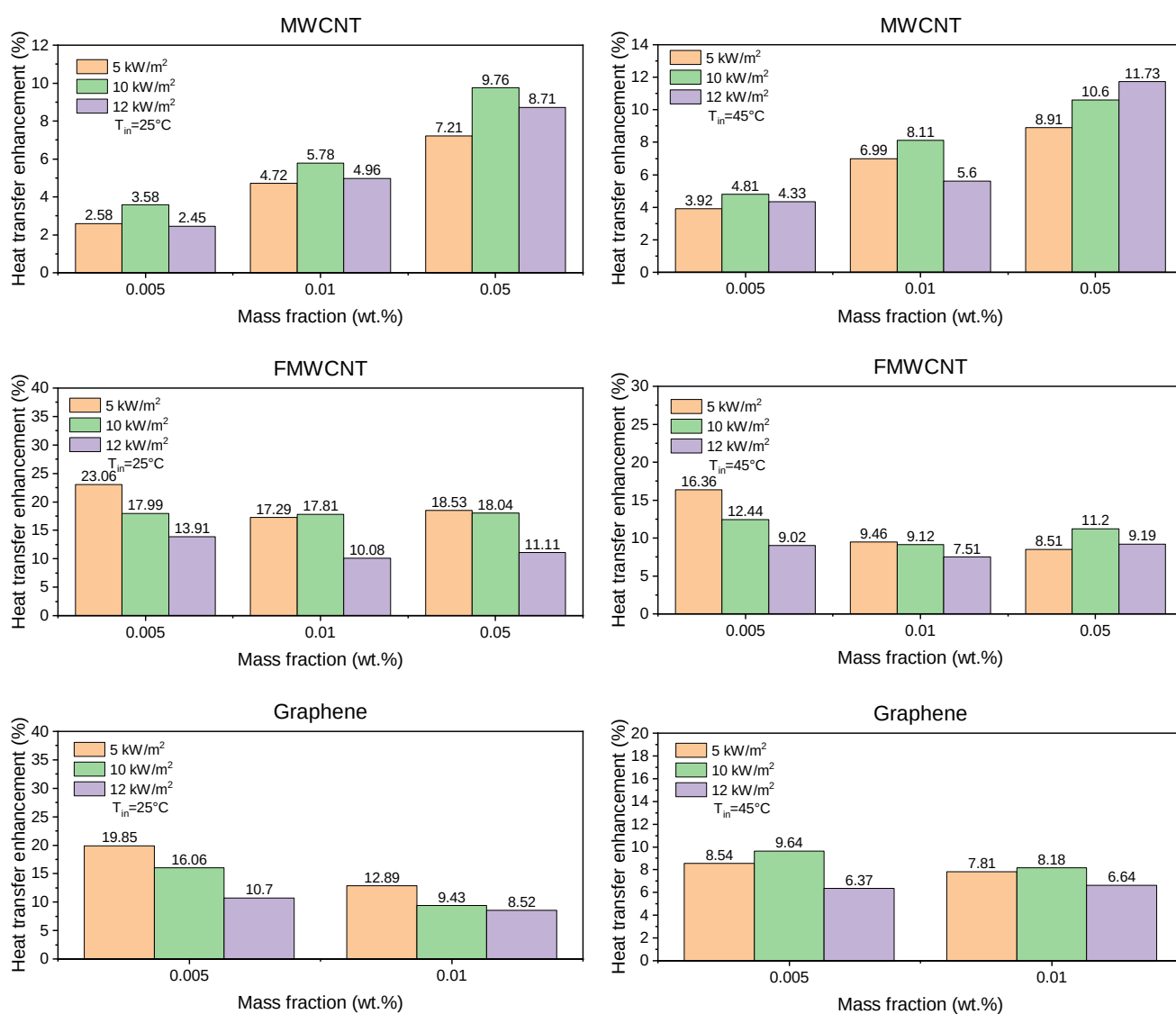


Figure 1H – Overall heat transfer enhancements for the straight pipe case with inlet temperature of 25 $^{\circ}\text{C}$ and 45 $^{\circ}\text{C}$ for all nanofluid samples. Source: Author's own.

APPENDIX I

Overall heat transfer enhancements for all nanofluid samples analyzed flowing under contraction, with CR = 1.4.

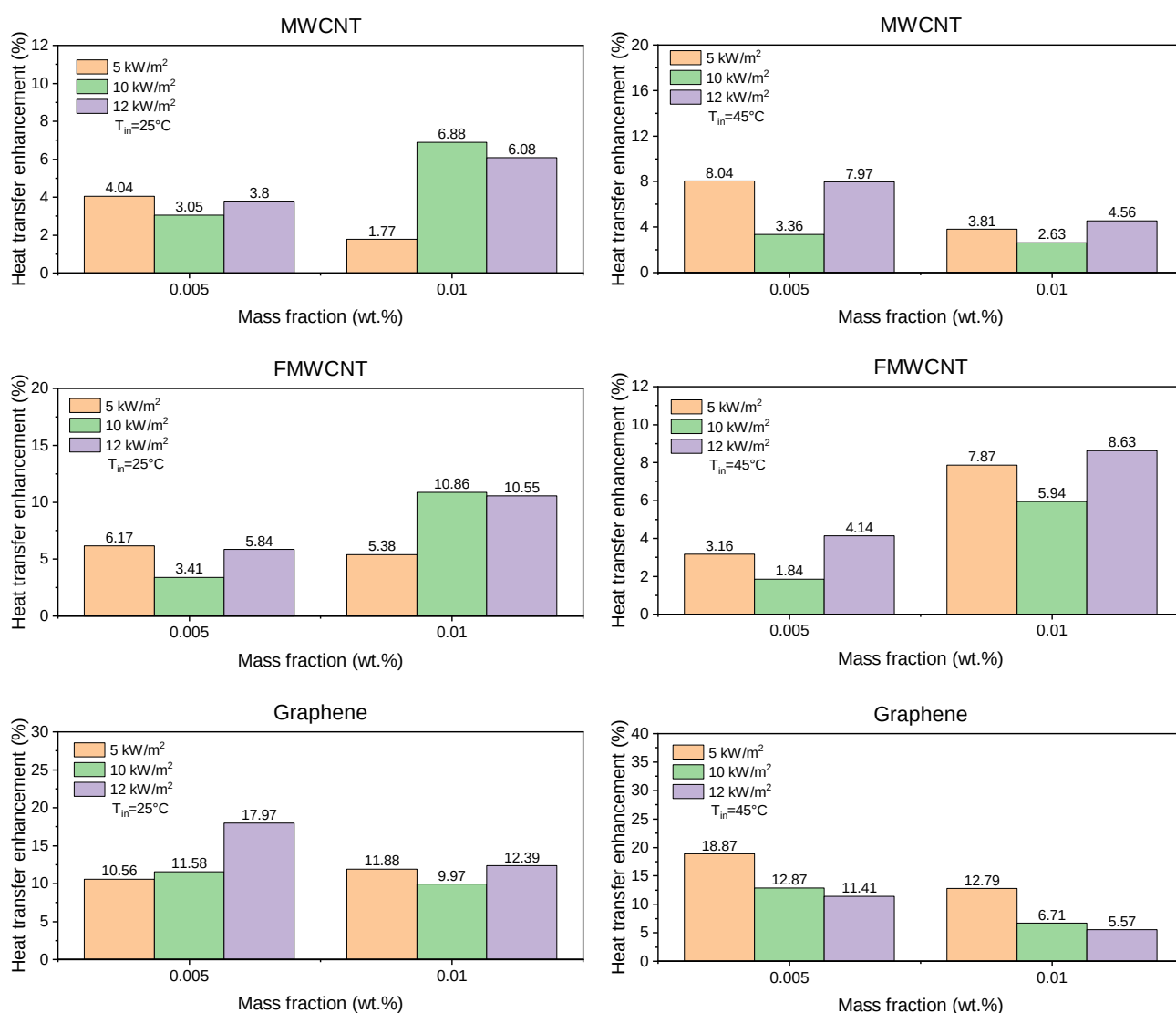


Figure 1I – Overall heat transfer enhancements for the nanofluids flowing under contraction (with CR = 1.4) with inlet temperature of 25 °C and 45 °C for all nanofluid samples. Source: Author's own.

APPENDIX J

Overall heat transfer enhancements for all nanofluid samples analyzed flowing under contraction, with CR = 1.9.

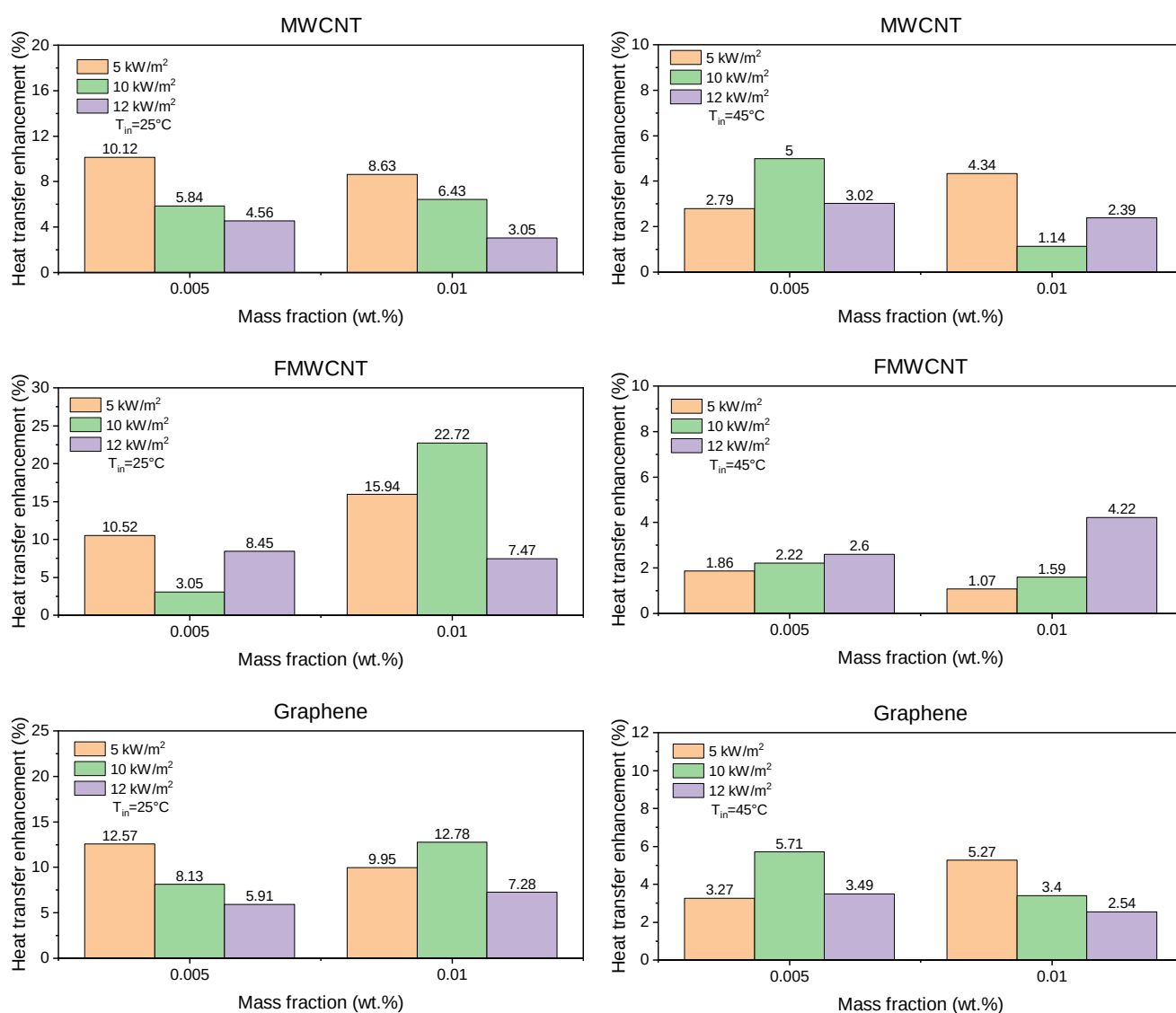


Figure 1J – Overall heat transfer enhancements for the nanofluids flowing under contraction (with CR = 1.9) with inlet temperature of 25 °C and 45 °C for all nanofluid samples. Source: Author's own.

APPENDIX K

Overall heat transfer enhancements for all nanofluid samples analyzed flowing under expansion, with $ER = 1.7$.

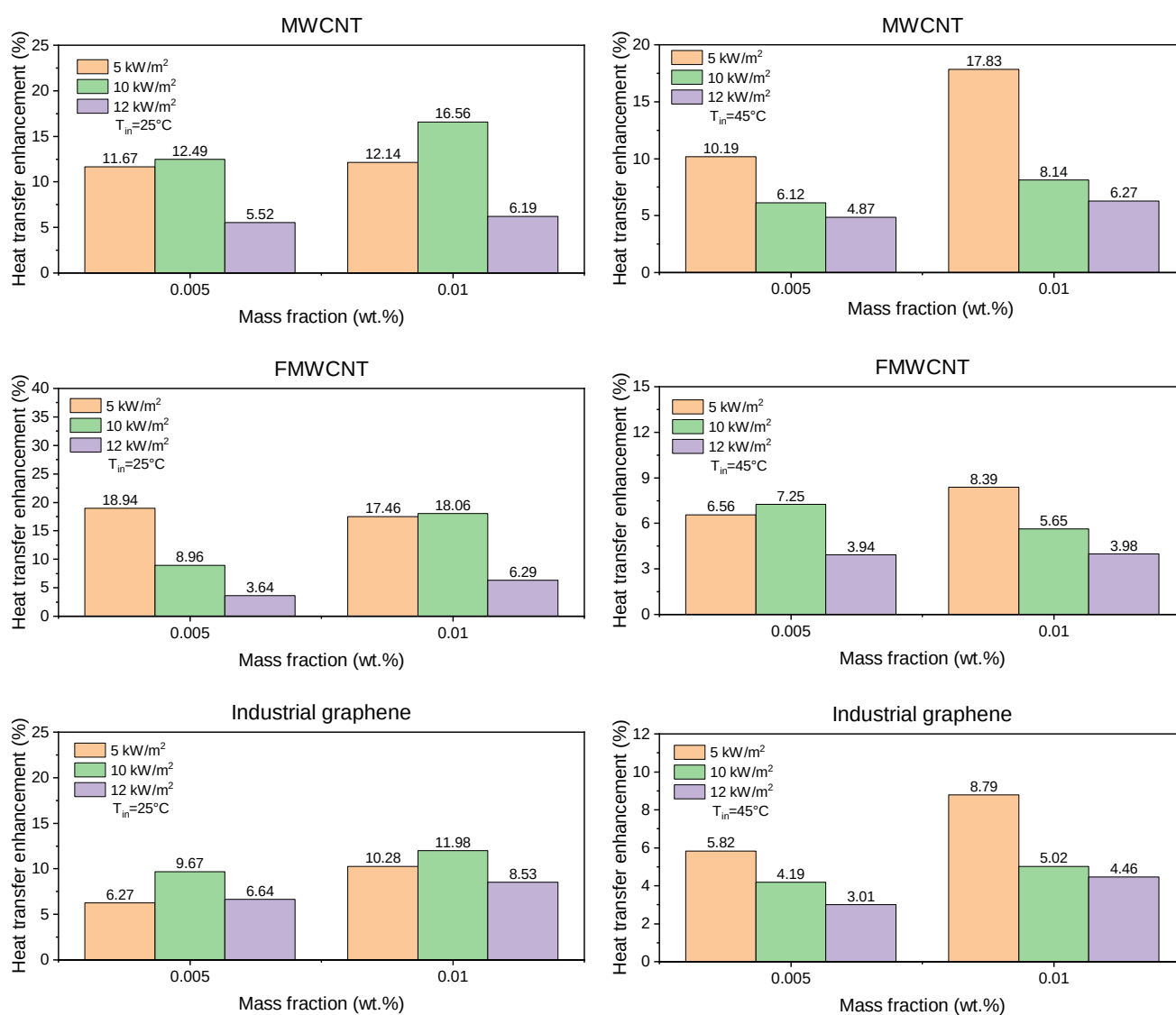


Figure 1K – Overall heat transfer enhancements for the nanofluids flowing under expansion (with $ER = 1.7$) with inlet temperature of 25°C and 45°C for all nanofluid samples. Source: Author's own.

APPENDIX L

Table 1K – Technical information of the oleic acid

Commercial name	Oleic Acid
Molecular Formula	$C_{18}H_{34}O_2$
Molar mass	281.4614 g/mol
Density	0.895 g/ml
Melting point	13 °C – 14 °C
Boiling point	360 °C (760 mm Hg)

Source: Author's own.

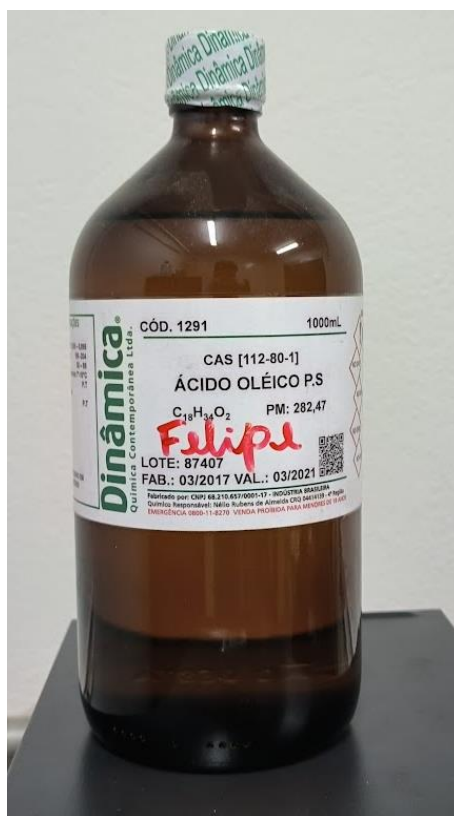


Figure 1K – Oleic acid used in the functionalization of carbon nanotube provided by *Dinâmica*.

Source: Author's own.